63 pages

DOE/NASA/0153-1
NASA CR-174734
84AEPD004

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MOD-5A Wind Turbine Generator Program Design Report

Volume I — Executive Summary

General Electric Company
(Advanced Energy Programs Department)

August 1984

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Center
Under Contract DEN 3-153

for
U.S. DEPARTMENT OF ENERGY
Conservation and Renewable Energy
Division of Wind Energy Technology

Printed in the United States of America

Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

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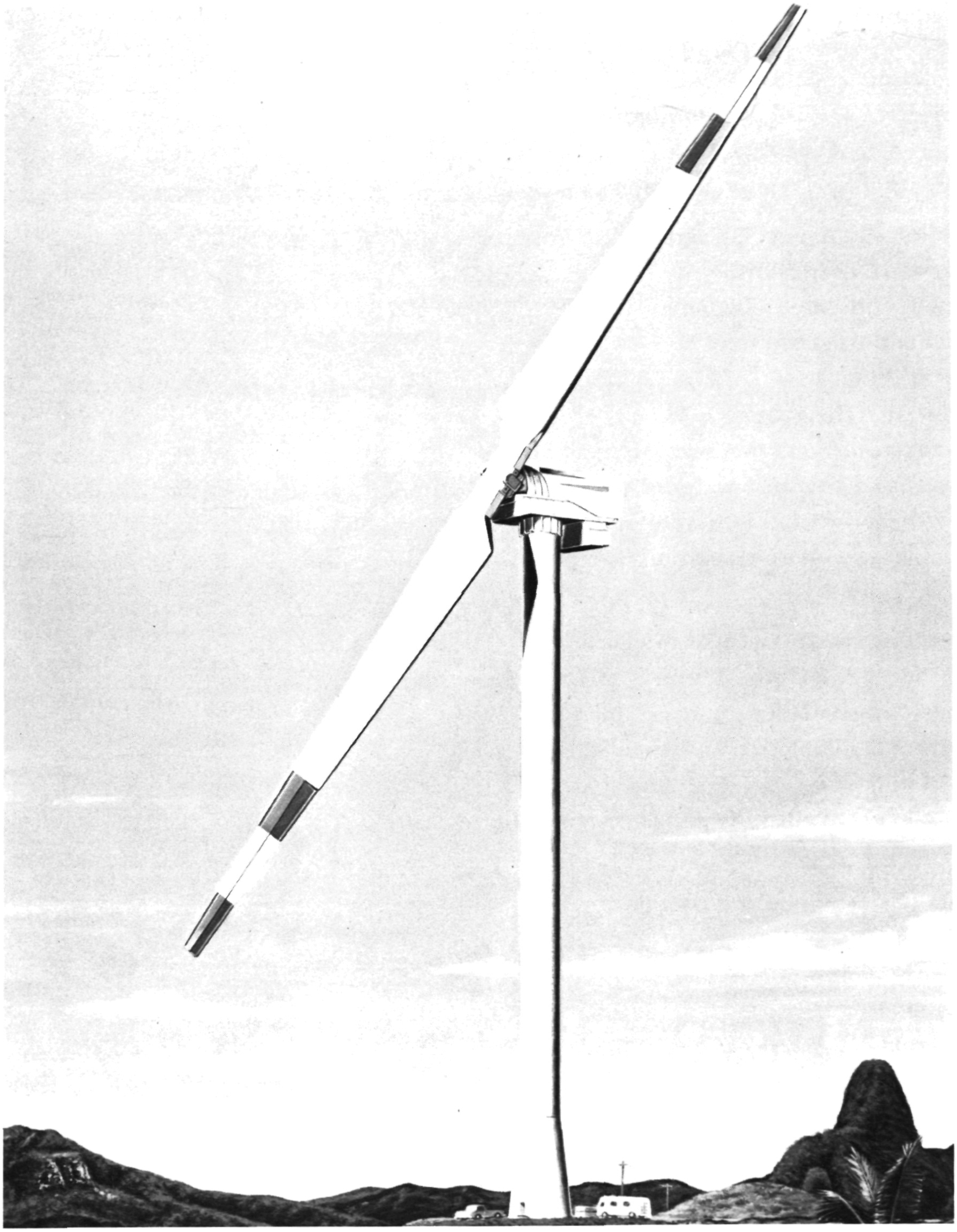

Rendition of the MOD-5A 7.3 MW Wind Turbine Generator, installed near Kahuku, Oahu, Hawaiian Islands.

INTRODUCTION

BACKGROUND

In 1973, a national Wind Energy Program was established to develop the technology to make wind energy systems cost competitive with conventional power generation systems, and to accelerate the commercialization and use of wind energy. The United States Department of Energy (DOE) directs this program. The NASA Lewis Research Center manages the development of large horizontal-axis wind turbines for the DOE.

The first large wind turbine constructed in the national wind program was the MOD-0. It was designed by NASA to provide early engineering data and to serve as a test bed for evaluating advanced wind turbine concepts. Testing of this 125 ft. diameter, 100 kW wind turbine began in 1975 at a site near Sandusky, OH. An improved version of this machine, uprated to 200 kW, was designed by NASA for integration into public utility networks. Four of these wind turbines, designated the MOD-OA, were installed and operated at Clayton, NM; Culebra Island, Puerto Rico; Block Island, RI; and Oahu Island, HI. Aluminum, wood, and glass fiber blades have been tested on the MOD-OA's.

In 1976, the General Electric Company was contracted to design and fabricate the first modern, megawatt class wind turbine. This system, called the MOD-1, had a 200 ft. diameter steel-bladed rotor and was rated at 2000 kW. It was installed and completed acceptance testing in Boone, NC during 1979.

The MOD-0, MOD-OA, and MOD-1 can all be classified as first-generation machines. Their prime objectives were to advance the state of technology and to gain experience operating in a utility environment. Common elements in all the designs were a downwind rotor with the blades rigidly attached to the hub, a stiff truss tower, and fully pitchable blades. At the end of the MOD-1 contract, GE performed a system's study to identify design features which would bring wind turbines closer to commercialization. A strawman design, called the MOD-1A, was developed. Notable features were a teetered rotor hub and blades in which only the tips were pitchable.

In 1977 the Boeing Company was contracted to design and build the MOD-2, a second-generation wind turbine. The design benefited from and expanded on past program experience. The final configuration, rated at 2500 kW, had a 300 ft. diameter steel-bladed rotor. It featured a teetered hub, pitchable blade tips, a soft, steel-shell tower, and an upwind rotor. Three units were installed in Goldendale, WA during 1980. Although a significant reduction in the cost of energy was realized with the MOD-2, further reductions in cost and design improvements were necessary for commercialization.

The MOD-5 program was established in 1980 to develop a third-generation wind turbine. The prototype design would build upon all the previous experience and supply the final bridge to commercialization. Two contracts were awarded — the MOD-5A to General Electric and the MOD-5B to Boeing.

The MOD-5A contract called for the design, development, fabrication, installation and operational checkout of an advanced, multi-megawatt wind turbine. The original program was restructured in mid-1981 to a cost-share arrangement. Fabrication, installation, and operation became the financial responsibility of GE and a utility customer which GE would

locate. General Electric was able to interest the Hawaiian Electric Company as the utility customer. A site for the MOD-5A with extremely good wind characteristics was identified in Hawaii. However, in December 1983, based upon extensive market research and world events which have made the near-future market for large wind turbines uncertain, GE made a decision to withdraw from this commercialization venture.

The MOD-5A program completed all the significant development tests and design work, and documented the entire program in Volumes I, II, and III of the MOD-5A Design Report. This volume contains an overview of the program which is discussed in detail in Volumes II and III. The contents of these volumes are listed in pages 40 through 57. Microfiche copies of these volumes are included in the back of this book.

OBJECTIVE AND DESIGN REQUIREMENTS

The objective of the MOD-5A program was to develop a reliable, commercially feasible wind turbine generator, with the following requirements:

- to be used as an electric utility power plant,
- rated at one megawatt or more,
- able to produce energy at less than 3.75 cents/kW-hr. in 1980 $ at a site with an average annual wind speed of 14 mph (this cost is the "busbar cost" for a cluster installation; it does not include transmission costs),
- to deliver three phase, 60 Hz power,
- to have a useful operational life of 30 years,
- configured with a horizontal-axis rotor.

APPROACH OF THE MOD-5A PROGRAM

The program began in July 1980. It was organized into three phases: Conceptual Design, which was completed in March 1981, Preliminary Design, which was completed in May 1982, and Final Design, which started in June 1982. Each design phase culminated in a comprehensive design review, which had two main objectives: to review the design's technical adequacy, and to verify that the requirement for cost of energy was still being met. Periodic reviews were also conducted by the User's Review Board, which had representatives from utilities, Electric Power Research Institute (EPRI), and GE's Power System Sector.

During the Conceptual Design phase, extensive trade-off and system sizing studies were conducted around a baseline configuration. The goal of these studies was to find a wind turbine concept with the greatest potential to meet the project's objective. A cost, cost of energy, and weight accounting procedure tracked the effects of the sizing and trade-off studies. In addition, a manufacturing plan was developed to determine costs for the fabrication of the 100th production unit.

After NASA and the DOE approved the conceptual design, the program progressed into the Preliminary Design phase. During this period the selected baseline configuration was analyzed in detail. Design refinements were made. Extensive development testing supported the design work by verifying new designs and determining the properties of new materials. By the end of Preliminary Design a thorough understanding of the system and its behavior had been derived. The Final Design phase was used to supply necessary details. It also focused on removing known elements of risk from the configuration. The outcome was a third-generation machine which met the goals of the program. The MOD-5A wind turbine was expected to produce energy at a cost competitive with the cost of conventional forms of power generation, when in volume production.

BIBLIOGRAPHY OF RELATED REPORTS

The MOD-5A program drew on the experience and information acquired during previous and concurrent wind energy research programs. The following is a bibliography of design reports resulting from DOE/NASA large wind turbine projects.

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"MOD-2 Wind Turbine System Development Final Report, Volume I — Executive Summary" by Boeing Engineering and Construction, NASA CR-No. 168006, DOE/NASA 0002-82/1, September 1982.

"MOD-2 Wind Turbine System Development Final Report, Volume II — Detailed Report" by Boeing Engineering and Construction, NASA CR-No. 168007, DOE/NASA 0002-82/2, September 1982.

"MOD-0A 200 kW Wind Turbine Generator Design and Analysis Report" by T.S. Andersen, C.A. Bodenschatz, A.G. Eggers, P.S. Hughes, R.F. Lampe, M.H. Lipner, and J.R. Schornhorst, Westinghouse Electric Corporation, Advanced Energy Systems Division, DOE/NASA/0163-2, NASA CR-165128, AESD-TME-3052, August 1980. N81-28516, 394 pages.

"MOD-0A 200 kW Wind Turbine Generator Engineering Drawing Report" by T.S. Andersen, C.A. Bodenschatz, A.G. Eggers, P.S. Hughes, and R.F. Lampe, Westinghouse Electric Corporation, Advanced Energy Systems Division, DOE/NASA/0163-3, NASA CR-165129, AESD-TME-3053, August 1980. N81-23598, 246 pages.

"MOD-2 Wind Turbine System Concept and Preliminary Design Report" Volume I — Executive Summary, by Boeing Engineering and Construction (A Division of The Boeing Company), Seattle, Washington, DOE/NASA/0002-80/2, NASA CR-159609. July 1979. N80-24758, 31 pages.

"MOD-2 Wind Turbine System Concept and Preliminary Design Report" Volume II — Detailed Report, by Boeing Engineering and Construction (A Divison of The Boeing Company), Seattle, Washington, DOE/NASA/0002-80/2, NASA CR-159609. July 1979. N80-26775, 269 pages.

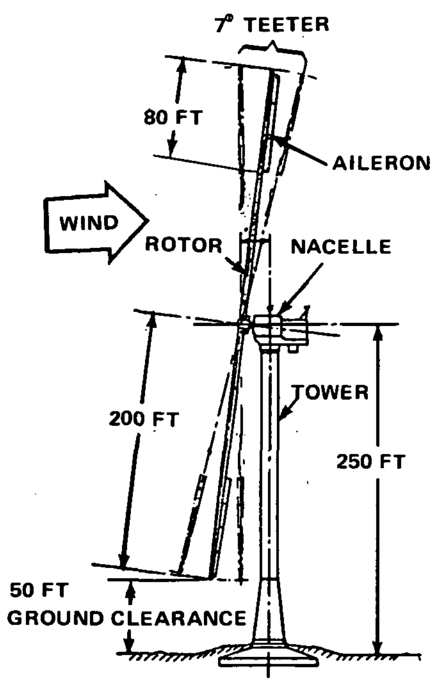
"MOD-1 Wind Turbine Generator Analysis and Design Report" General Electric Co., Space Division, Philadelphia, PA, Contract NAS3-20058, DOE/NASA/0058-79/2 — Volume 1, NASA CR-159495, May 1979. N80-23775, 320 pages.

"Executive Summary MOD-1 Wind Turbine Generator Analysis and Design Report" NAS3-20058. DOE/NASA/0058-79/3, NASA CR-159497, General Electric Space Division, March 1979. N80-11558, 61 pages.

DESCRIPTION OF THE FINAL DESIGN

GENERAL DESCRIPTION

The final design of the MOD-5A pictured in Figure 1 is a 7.3 MW wind turbine generator which will produce 21.2GW-hr per year at a site having a 14 mph mean wind speed. The MOD-5A has a 400 ft. diameter, two-bladed, teetered rotor, which is located upwind of the tower. The rotor shaft is tilted 7° to provide clearance between the blades and tower. The blades are made of epoxy-bonded wood laminates. This construction is an outgrowth of successful MOD-0A applications. Hydraulically actuated ailerons over the outboard 40% of the blade span are used to regulate power and control shutdown. The blades are supported on elastomeric teeter bearings located in the ears of a welded steel yoke. Views of the yoke, its support, and interfacing components mounted in the nacelle are provided in Figure 2 and 3. The yoke rotates on two rows of internal roller bearings which are housed on a non-rotating spindle bolted to the nacelle. The spindle reacts all rotor loads except torque, which is transmitted through the low speed shaft to the gearbox. The gearbox provides an 82.14:1 stepup ratio in going from the rotor to the generator. This is accomplished with three stages of speed increasers, the first two of which are epicyclic, while the third is a conventional parallel shaft. The generator is a 7500 kVA six-pole wound rotor machine. It is designed to operate at variable speed. Constant 60 Hz output frequency is maintained by a cycloconverter which is located in a ground enclosure near the base of the tower. The generator also serves as a motor during startup. Electrical power is transmitted between the rotatable nacelle and stationary tower by the



OPERATIONAL CHARACTERISTICS

RATED POWER	7300 KW
RATED WIND SPEED	32 MPH AT 250 FT
CUT-IN/CUT-OUT WIND SPEED	14/60 MPH AT 250 FT
MAXIMUM WIND SPEED	130 MPH AT 250 FT
ROTOR SPEED	
14-25 MPH WIND	13.5 ± .3 RPM
22-60 MPH WIND	16.5 ± .3 RPM
POWER AND SPEED CONTROL	MULTI-SECTION AILERONS
ENERGY CAPTURE/YR	21.2 X 10^6 KWH
SYSTEM AVAILABILITY	96%
TOTAL WEIGHT ON FOUNDATION	1804 K-LB

FEATURES

- LAMINATED WOOD BLADES WITH HIGH PERFORMANCE AIRFOIL - UPWIND, TEETERED
- NON-ROTATING ROTOR SUPPORT
- HYBRID EPICYCLIC/PARALLEL SHAFT GEARBOX
- VARIABLE SPEED/CONSTANT FREQUENCY OPERATION WITH 2 SET POINTS
- SOFT SHELL TOWER, TUNEABLE CONICAL BASE

FIGURE 1. MOD-5A FINAL DESIGN (MODEL 304.2)

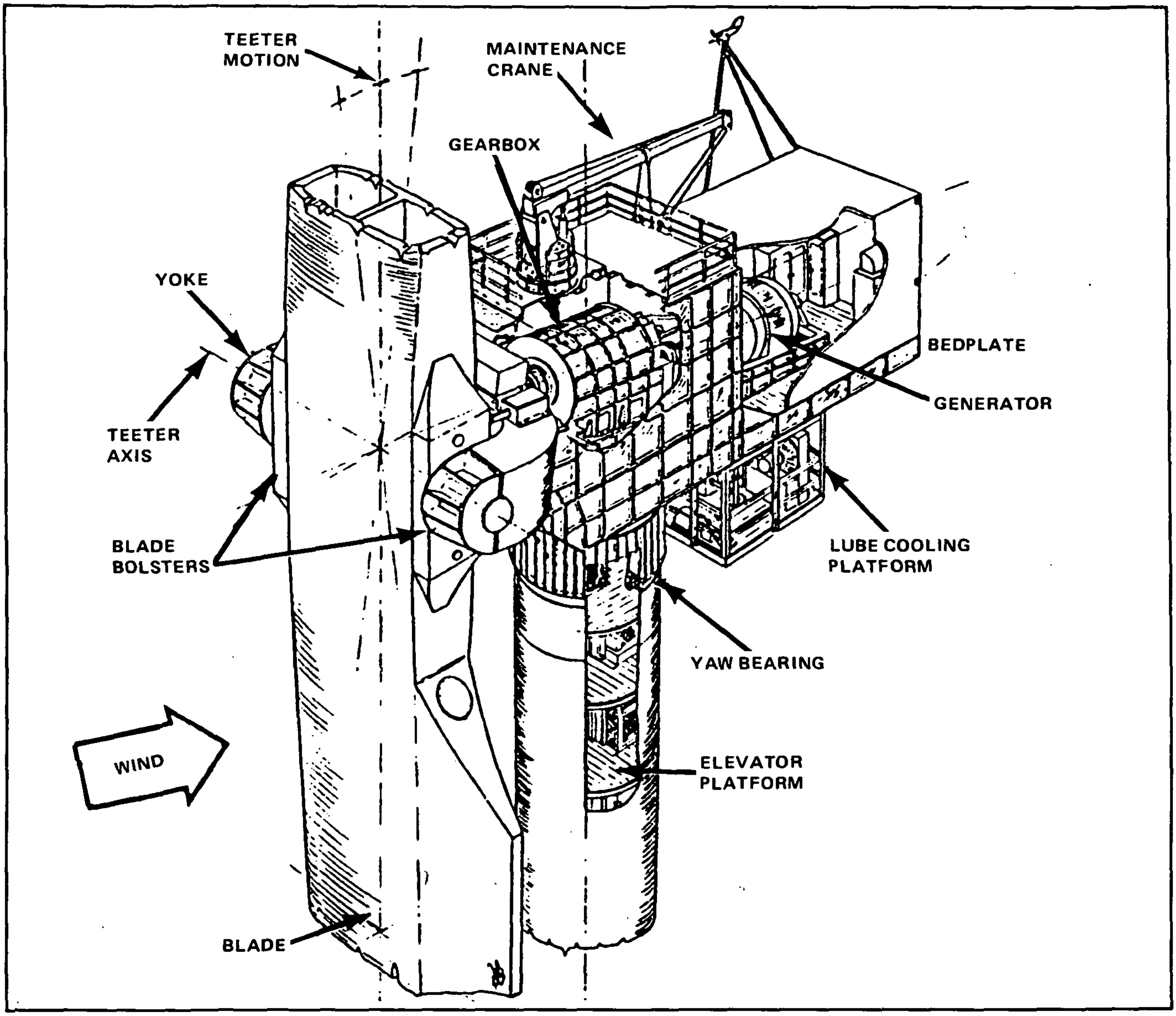


FIGURE 2. DETAIL OF TOWER, NACELLE AND ROTOR

yaw slipring. The nacelle supports the gearbox, generator and auxiliary hardware using a bedplate type construction consisting of welded steel plate and standard structural shapes. Proper alignment with the wind is maintained by rotating the nacelle about the yaw bearing which is housed at the top of the cylindrical tower. The yaw drive is comprised of a hydraulically-actuated disc brake system. A similar yaw drive was used successfully on the MOD-0A in Hawaii. The tower is a welded steel plate cylindrical shell with a conical base. It is a soft design in that the fundamental bending frequency is below the two per revolution forcing frequency of the rotor.

The MOD-5A is designed to operate in wind speeds from 12 to 60 mph (at hub height). The machine is started when the wind speed exceeds 14 mph using the generator to motor the rotor to 3.7 rpm, after which the ailerons are used to attain the desired operating speed. It is shutdown when the wind speed exceeds 60 mph or goes below 12 mph. Shutdown is accomplished by feathering the ailerons 90°, which will slow the rotor to 6 rpm or less,

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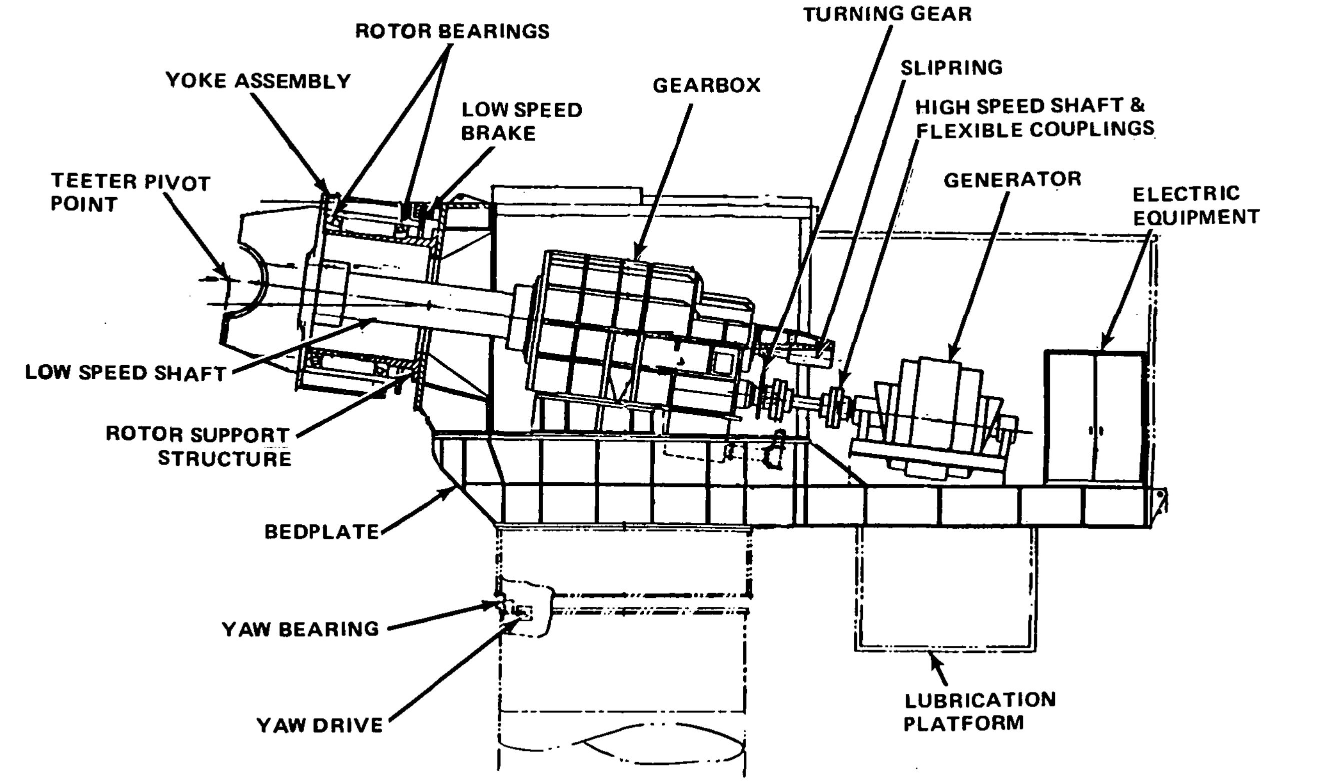

FIGURE 3. CUT-AWAY VIEW OF NACELLE SHOWING ROTOR SUPPORT AND DRIVETRAIN ELEMENTS

depending on the wind speed, and then applying a low speed brake to bring the rotor to a complete stop. There are two narrow ranges of normal operating rpm. At low wind speeds the rotor speed varies between 13.2 and 13.8 rpm depending on the power output. At higher wind speeds the range is from 16.2 to 16.8 rpm. These operating bands were selected to maximize energy capture, yet avoid structural resonances. They are resettable in the field with the variable speed generator system. Rated power is produced at 32 mph. Above this wind speed, the ailerons are deflected to maintain the 7.3 MW rated output. Yaw corrections are made if the misalignment with the incoming wind exceeds 7°.

The system was designed for automatic, unattended operation. It has a design life of 30 years and production units are projected to generate electricity at 3.69¢/ kW-hr in 1980 dollars when installed in clusters of 24 units. System weights and features are highlighted in Table 1.

POWER AND ENERGY OUTPUT

The power output is shown as a function of wind speed in Figure 4. Regions of the two-speed operation are indicted. The transition from low rpm to high rpm occurs at 25 mph, while the transition from high rpm to low rpm occurs at 22 mph. This hysteresis in the operating strategy avoids frequent shifting. The variable speed generator accomplishes the rotor speed changes while power is being delivered. The two-speed operation allows the rotor to operate near peak efficiency from 17-32 mph which comprises 70% of the total operating

TABLE 1. MOD-5A FINAL DESIGN (MODEL 304.2)

SYSTEM WEIGHT, EXCLUDING FOUNDATION	1,804,000 LB
INSTALLED COST FOR THE 100TH UNIT	$4,112,000 (1980$)
ANNUAL ENERGY OUTPUT, 96% AVAILABILITY*	21.2 GW-HR
COST OF ENERGY FOR THE 100TH UNIT	3.69 ¢/KW-HR (1980$)

ROTOR 474,000 LB.

- UPWIND OF TOWER
- 400 FT. DIAMETER
- LAMINATED WOOD BLADES
- 13.2-13.8/16.2-16.8 RPM TWO-RANGE, VARIABLE SPEED OPERATION
- 352 FT/SEC TIP SPEED, AT 16.9 RPM
- CONTINUOUS WOOD BLADE, TIP-TIP
- 64-XXX AIRFOIL, 300 IN. ROOT CHORD, 3.94% SOLIDITY
- 40% (80 FT.) AILERON CONTROL –90° MOTION 40% CHORD, 3 HYDRAULIC ACTUATORS/BLADE
- STEEL YOKE ATTACHMENT AT TEETER AXIS
- TEETER AND BRAKE SHAFTS IN BOLSTER
- ROTOR STOPPING BRAKE
- YOKE-MOUNTED HYDRAULIC POWER UNIT
- 7° TILT, ±9° TEETER ALLOWANCE
- ELASTOMERIC TEETER BEARINGS AND BRAKE-TYPE TEETER RESTRICTOR.
- YOKE SUPPORTED ON SPINDLE WITH DUAL BEARINGS

DRIVETRAIN 260,000 LB.

- FLOATING TORQUE SHAFT FROM YOKE TO GEARBOX
- HYBRID SINGLE RATIO GEARBOX, 3.38 MILLION FT.-LB. INPUT TORQUE
- PLANETARY 1ST AND 2ND STAGE GEARING, PARALLEL SHAFT 3RD STAGE
- IN-LINE SLIPRING ACCESS, SHAFT DRIVE LUBE PUMP, INCHING DRIVE
- FLOATING HIGH SPEED SHAFT, FROM GEARBOX TO GENERATOR

FOUNDATION

- SPREAD FOOTING, REINFORCED CONCRETE
- ABOUT 960 CUBIC YARDS
- ANCHOR BOLTS FOR TOWER ATTACHMENT

NACELLE 329,000 LB.

- BEDPLATE WITH WIRING, PIPING UNDER FLOORING
- BOX-TYPE ROTOR SUPPORT STRUCTURE WITH SPINDLE, CRANE MOUNT
- MOUNTINGS FOR GEARBOX, GENERATOR, CONTROL ELECTRONICS, HIGH VOLTAGE CABINET
- INSULATED WEATHER FAIRING
- LUBRICATION SYSTEM FOR GEARBOX AND BEARINGS ON LOWER PLATFORM
- HYDRAULIC POWER SUPPLY AND PUSH-PULL YAW DRIVE
- YAW SLIPRING

TOWER 653,000 LB.

- 14.5 FT. DIAMETER STEEL SHELL
- 250 FT. TO ROTOR HUB
- 50 FT. CONICAL BASE FOR TUNING
- YAW STRUCTURAL ADAPTERS AND BEARING
- INTERNAL TRACTION ELEVATOR AND LADDER

ELECTRICAL, 88,000 LBS.

- GENERATOR: VARIABLE SPEED, CONSTANT FREQUENCY
- POWER: 5000 KW AT 960 RPM, 7500 KW AT 1440 RPM
- MOTORING SPEEDS: 0-300 RPM
- 175 MVA RADIAL FEEDER CLUSTER, WITH 24 UNITS
- 69 KV RATED INTERFACE
- ELECTRICAL EQUIPMENT BUILDING WITH CYCLO-CONVERTER AND SWITCHGEAR AND CONTROL
- 7,300 KVA, OIL-FILLED TRANSFORMER WITH FUSED SWITCH

MAINTENANCE

- PERMANENT CLUSTER CREW

*ANNUAL AVERAGE WIND SPEED OF 14 MPH AT 32 FT., WITH NASA SPECIFIED WIND DURATION CURVE.

time. This results in approximately 3% more energy capture than is possible with a single speed wind turbine.

The power output characteristics in Figure 4 were used to compute the annual energy output. The predicted annual energy capture at 96% availability is 21.2 GW-hr per year. Table 2 contains a detailed account of energy losses associated with this net annual output. The predictions are based on the wind characteristics supplied in the MOD-5A Statement of Work. It refers to a site having a 14 mph average wind speed at 10m above ground.

The first MOD-5A wind turbine was to be built in Kahuku, Oahu, Hawaii. The annual energy capture for the wind in Kahuku, at 96% availability, is predicted to be 32.2 GW-hr. The strong trade winds in Kahuku provide almost 2.5 times the operating time at rated power provided by the design wind, and consequently the energy capture is much greater.

COST AND COST OF ENERGY

The summaries of cost and cost of energy for the first, the 100th unit in a single installation, and the 100th unit in a cluster installation are shown in Table 3. The predicted cost of energy

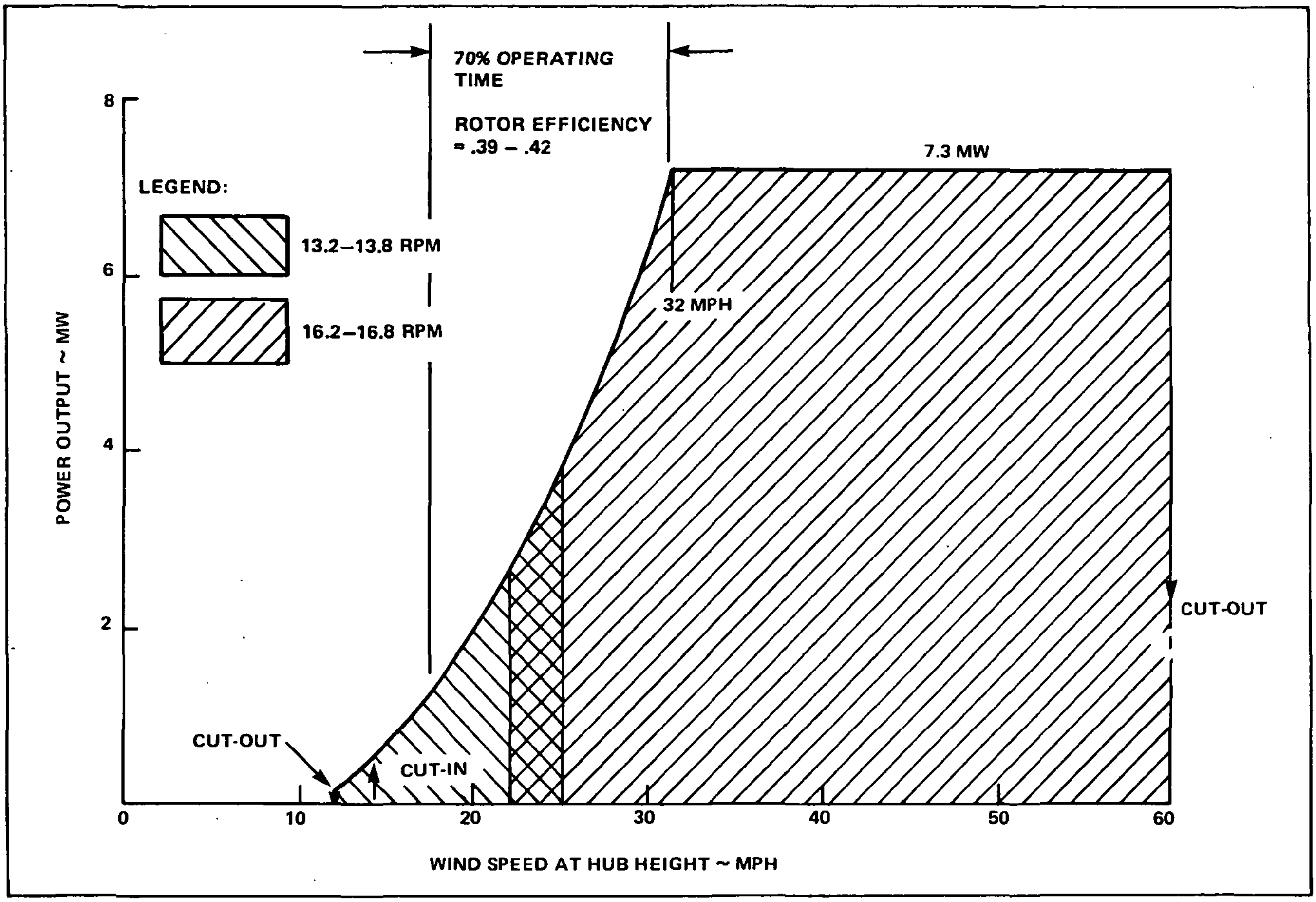

FIGURE 4. MOD-5A DESIGN POWER CURVE

for the clustered installation, in volume production, for the design wind and an availability of 96%, is 3.69 cents/kW-hr. This cost is below the maximum of 3.75 cents/kW-hr, which was a requirement of this program.

Several assumptions were made in the calculation of these costs. All costs were calculated in 1980 dollars. Costs for major components, such as the rotor, tower and gearbox, were based on prices quoted in preliminary bids. The costs for the 100th unit in a clustered installation were calculated assuming that the unit was built in a dedicated plant, that spare parts are stocked in a regional inventory, and that the product is a mature design. The cost of energy is computed as follows:

$$\text{Cost of Energy} = \frac{\text{Levelized Annual Cost}}{\text{Annual Energy Output}}$$

The levelized annual cost includes:

- Capital cost at a fixed charge rate of 0.18
- Land cost at a fixed charge rate of 0.15
- Operating and maintenance cost at a levelizing factor of 2.0
- Periodic replacement levelized cost

The annual energy output takes into account:

- System power characteristics
- System losses
- Specified wind curve, with average annual speed of 14 mph at 32 ft
- Scheduled and unscheduled maintenance

ROTOR SUBSYSTEM

The rotor subsystem consists of the blades, ailerons, yoke and rotor support. A teetering rotor was selected for the MOD-5A as it was

TABLE 2. MOD-5A NET ENERGY OUTPUT AND SYSTEM LOSSES

ITEM (MODEL 304.0)	ENERGY LOSS -GWH/YEAR	NET ENERGY OUTPUT GWH/YEAR
GROSS WIND ENERGY (12-60 MPH)		72.34
• NOT EXTRACTABLE	29.44	
MAXIMUM THEORETICAL ENERGY (BETZ LIMIT)		42.90
• ROTOR PROFILE DRAG AND DETERIORATION	11.60	
• ROTOR POWER LIMIT (ABOVE RATING)	4.57	
• ROTOR TEETER, TILT, HEADING, MISC.	1.44	
• ROTOR STARTUP, SHIFTING LOSSES (1100/YR @ 15 MIN. EACH)	0.29	
ROTOR OUTPUT ENERGY		25.00
• TRANSMISSION LOSSES	1.06	
• GENERATOR LOSSES	0.99	
GENERATOR OUTPUT ENERGY		22.95
• ACCESSORY/AUXILIARY LOSSES	0.58	
• TRANSFORMER LOSSES	0.11	
SINGLE UNIT OUTPUT ENERGY		22.26
• INTERCONNECTION LOSSES	0.21	
• AVAILABILITY LOSSES @ 96% AVAILABILITY	0.86	
NET UTILITY SUBSTATION OUTPUT ENERGY		21.19

for the earlier MOD-2 machine, because it reduces rotor dynamic loads. The blades are free to rotate or teeter as a unit about a central axis passing through the yoke as indicated in Figure 2. This freedom eliminates large vibratory bending moments that would otherwise be transmitted to the yoke. Loads on the inboard portions of the blade are similarly reduced.

Reliability and safety are enhanced by structurally efficient load paths within and among the various elements. The primary load carrying structure of the assembled light-weight wood blades is continuous from tip to tip. This is possible for two reasons. First, the blades are supported by a yoke, which surrounds, rather than penetrates the center blade. Second, the use of ailerons rather than a pitchable tip (or blade) for torque control has eliminated spanwise discontinuities. The continuous primary wood structure reacts all centrifugal, aerodynamic bending and gravitational bending loads. Only rotor torque and shears, primarily due to gravity, are transmitted to the yoke.

A further improvement over past designs is the method of rotor support shown in Figure 3. The inner interface is a non-rotating spindle, which is bolted to the nacelle. It sees the weight of the rotor as a constant steady load. Fatigue loading is relatively low on this piece. The outer rotating interface is an integral part of the yoke structure. It experiences cyclic stresses due to the weight of the rotor as any rotating shaft would. By locating the rotor bearings close to the center of gravity, rather than in the nacelle, the vibratory bending moments on this rotating piece are minimized. Additional structural efficiency was derived by placing the more critical rotating piece on the outside, giving it inherently greater load carrying capability. An independent load path is provided to transmit

TABLE 3. COST SUMMARIES FOR THE FIRST UNIT, AND THE 100TH UNIT IN SINGLE AND CLUSTERED INSTALLATIONS

	FIRST UNIT		100TH UNIT, SINGLE INSTALLATION		100TH UNIT, CLUSTERED INSTALLATION	
	COST (1980 $)	CONTRIBUTION TO COST OF ENERGY (1980 ¢/KWH)	COST (1980 $)	CONTRIBUTION TO COST OF ENERGY (1980 ¢/KWH)	COST (1980 $)	CONTRIBUTION TO COST OF ENERGY (1980 ¢/KWH)
SITE PREPARATION	$ 1,248,400	1.132	$ 682,532	0.580	$ 658,208	0.560
TRANSPORTATION	306,854	0.278	239,156	0.203	179,816	0.153
ERECTION	1,799,900	1.633	254,548	0.216	214,548	0.182
ROTOR	3,934,970	3.569	864,811	0.735	864,811	0.735
DRIVETRAIN	1,125,571	1.021	539,527	0.459	539,527	0.459
NACELLE	1,376,864	1.249	480,935	0.409	480,935	0.409
TOWER	858,633	0.779	542,588	0.461	484,161	0.412
REMOTE CONTROL	5,504	0.005	3,212	0.003	3,212	0.003
SPARES	117,496	0.107	75,862	0.065	33,716	0.029
PROFIT/ASSEMBLY AND TESTING	1,928,907	1.750	481,324	0.409	458,901	0.390
LAND	0	0.000	5,923	0.004	5,923	0.004
CLUSTER	0	0.000	181,594	0.154	181,594	0.154
INSTALLED COST	$12,703,099		$4,352,012		$4,105,352	
ANNUAL OPERATING AND MAINTENANCE	46,428	0.438	25,016	0.236	20,988	0.198
COST OF ENERGY		11.960		3.935		3.688

rotor torque from the yoke to the low speed shaft.

Other distinguishing features of the MOD-5A rotor include:

- high performance aerodynamic characteristics developed from extensive airfoil testing
- cost and weight savings derived by the use of ailerons rather than a pitchable tip section for torque control
- the use of all wood finger joints to glue spanwise sections of the blades together rather than the wood-steel stud interface used in previous designs

Blades

The blade external geometry is pictured in Figure 5. The planform tapers linearly from a 73 in. chord at the tip to a maximum width of 300 in. at 25% radius. The high performance NACA 64-XXX airfoil, which is suited to thicker sections, was selected for the MOD-5A. The airfoil has a 15% thickness to chord ratio at the tip and increases to 29% at 25% span. Thick sections were required for structural efficiency. Because the inboard blade thicknesses are greater than those used in aeronautical applications, extensive wind tunnel testing was performed to characterize and optimize the thick sections. Reductions in profile drag were derived with the raised, finite thickness, trailing edge shown in Figure 6. Fabrication techniques limited the amount of built-in geometric twist to 5°. This was augmented by transitioning from a highly cambered 64-615 airfoil section at the blade tip to a symmetrical 64-029 airfoil at 25% span. The change in camber increases the effective aerodynamic twist to approximately 10°, which is well suited for the MOD-5A application.

Figure 7 depicts the material arrangement in the typical blade cross-sections shown in Figure 6. The structural portion of the airfoil shell is

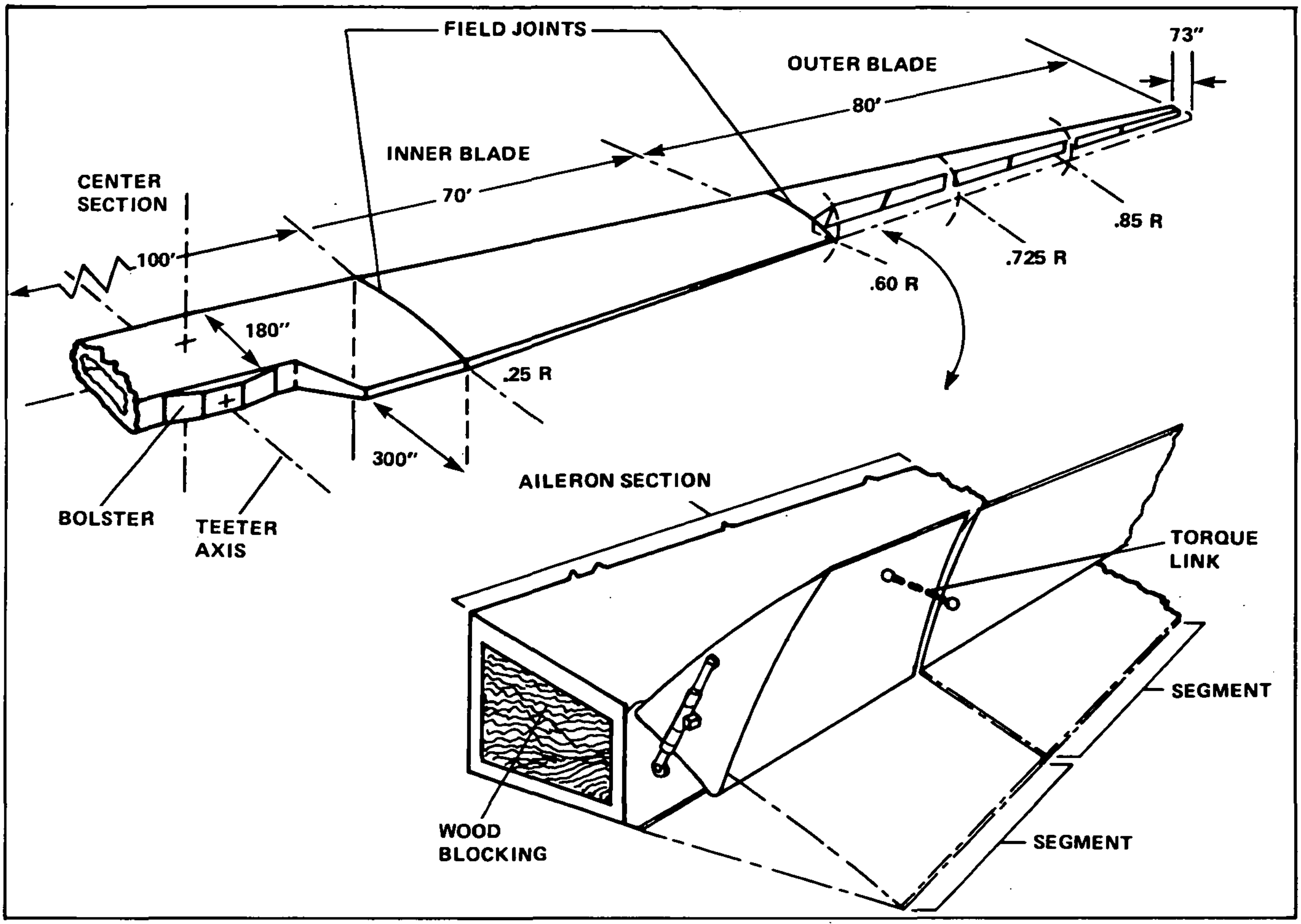

FIGURE 5. MOD-5A BLADE ASSEMBLY

made from laminae of 0.10 in. thick Douglas fir bonded with epoxy. The non-structural trailing edge is bonded to the 0.60C spar. It has a paper honeycomb core with glass fiber facia. A 30-mil layer of glass fiber cloth covers the exterior and interior surfaces to provide environmental protection and a smooth exterior finish. Aluminum screening and metal leading edge strips are embedded beneath the glass fiber layer for lightning protection.

The blades are fabricated in five major subassemblies to meet shipping requirements. The 100 ft. center section is common to both blades. Each blade then has a 70 ft. inner section and 80 ft. outer section as indicated in Figure 5. The subassemblies are bonded together at field joints which are in the pattern of fingers. The finger joints were developed during the MOD-5A program to provide joint efficiencies approaching that of continuous wood.
With this wood to wood interface, the problem associated with dissimilar material joints are avoided. The non-structural trailing edge and ailerons are also fitted in the field. The total weight of the assembled blades, inclusive of the ailerons, is 270,000 lb.

Rotor torque and shear loads are transmitted to the yoke through bolsters which are bonded to the side faces of the center blade. The bolsters, shown in Figure 8, are made of alternate layers of Douglas fir veneer and bidirectional glass fiber cloth. Three holes are built into each bolster. The center hole provides clearance for the teeter shaft and a cavity to

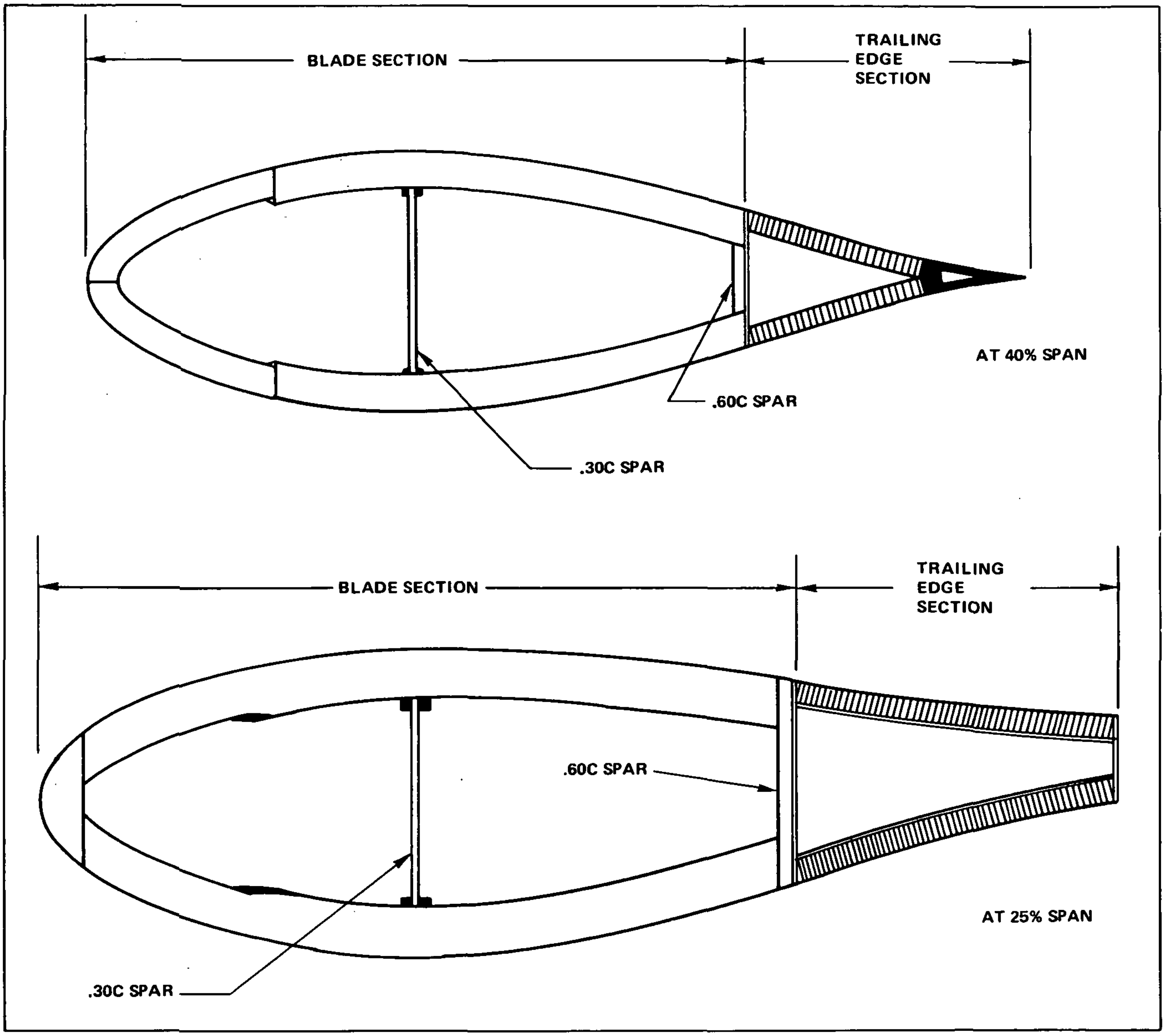

FIGURE 6. TYPICAL BLADE CROSS-SECTIONS

install the radial teeter bearing fitting. The remaining holes are used to install fittings for the teeter brake assembly. The brakes are required to restrict teeter motion while parked and at low rpm. They are disengaged during power producing operation.

Blade fabrication was subcontracted to Gougeon Brothers, Inc. They have worked with NASA on previous wind turbine blade development programs and have constructed laminated wood/epoxy blades for the MOD-OA. These were successfully operated on the MOD-OA wind turbines in Hawaii, Culebra, and Block Island.

Ailerons

The ailerons, depicted in Figure 5, extend from 60% to 99% of the blade span. They comprise the rearward 40% of the airfoil section and can pivot -90° about the hinge axis. The ailerons are divided into three sections, each of which are divided into two segments. The inboard segments of each section are driven by a linear hydraulic actuator. Each pair of segments are connected by a torque link that slaves the

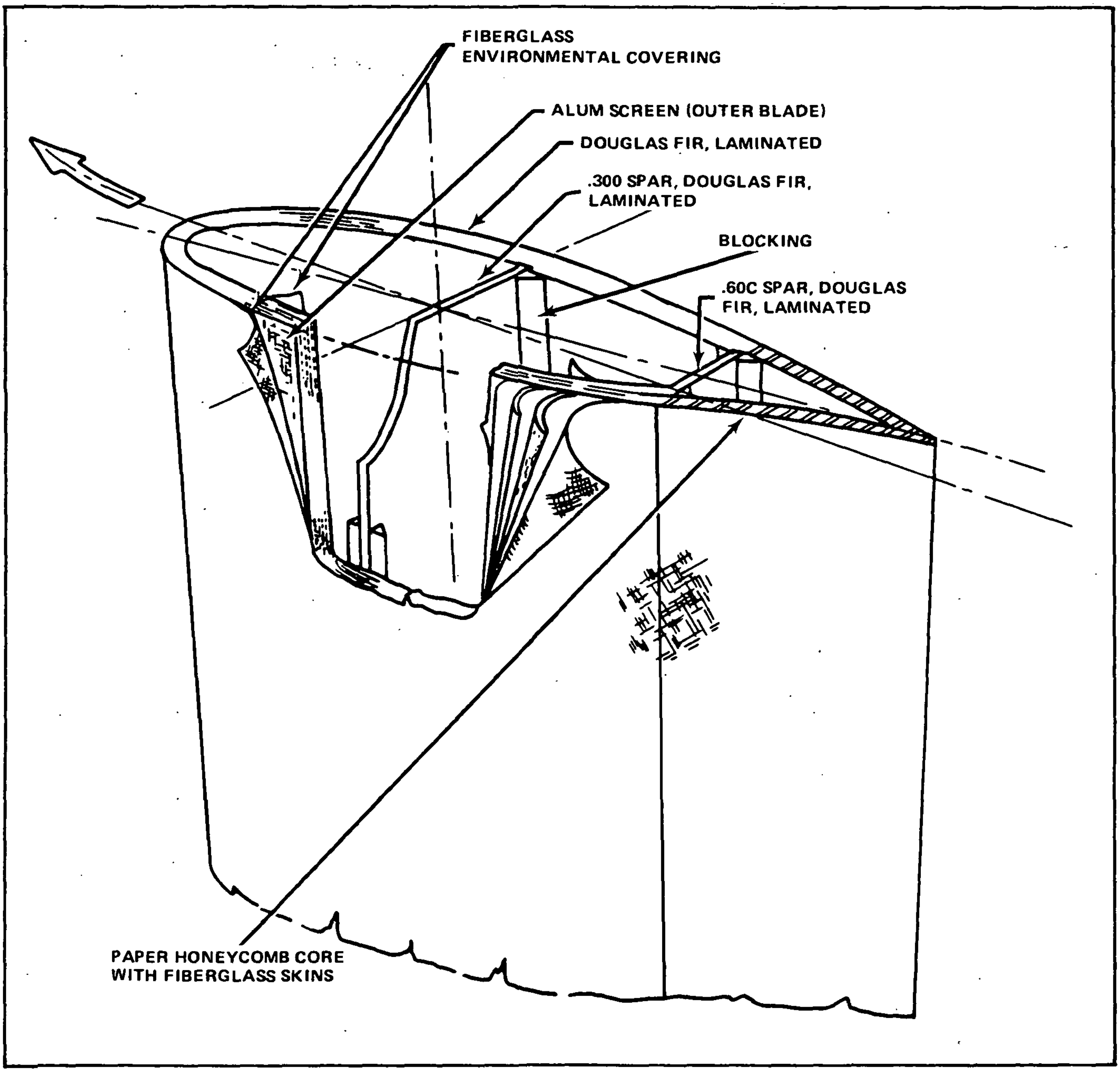

FIGURE 7. BLADE MATERIALS ARRANGEMENT

pitching rotation of the outer segment to the inner. The ends of the link are mounted in spherical bearings which permit independent axial and radial alignment of each segment with the blade. All actuators are driven in phase such that all ailerons have the same pitch deflection.

The ailerons are affixed to the main blade in spherical self-aligning bearings located at the inboard and outboard ends of each segment. Centrifugal loads are reacted at the inboard bearings. Axial freedom is provided at the outboard end to compensate for misalignment, thermal expansion and main blade deflections. The bearing fittings are attached to the main blade with steel studs. These studs are bonded into four inch thick wood ribs, which occupy the blade cross-section at these locations.

The segmented aileron design was selected because the shorter span between support points reduces the aileron bending stresses and

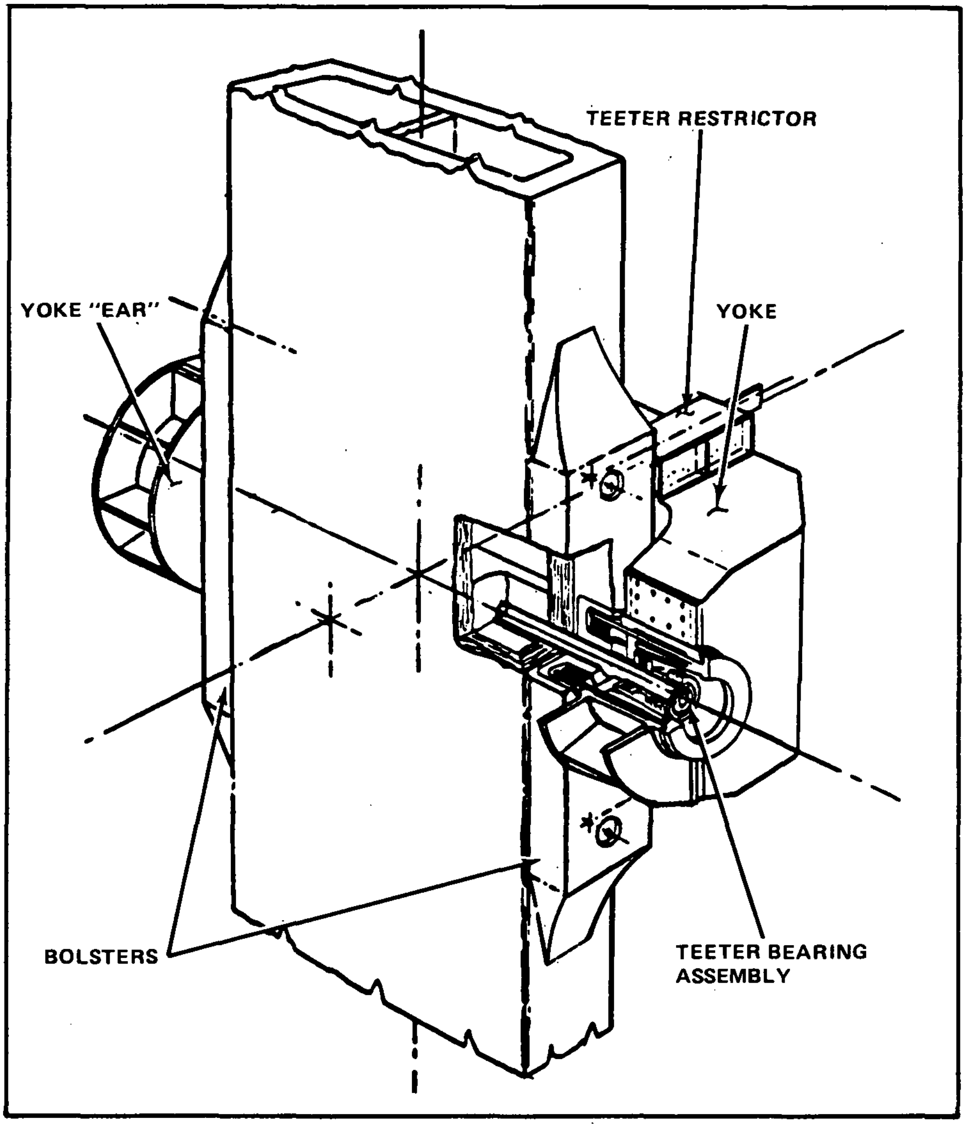

FIGURE 8. BLADE BOLSTERS AND TEETER ASSEMBLY

because the shorter segments can more readily conform to blade deflections. An additional advantage is that the point loadings on the main blade are distributed over more attachment locations. Three, rather than fewer, sections were chosen because they reduce the load per actuator and actuator size. More important, aileron elastic torsional deflections are limited to acceptable amounts because of the shorter unsupported length outboard of the actuators.

A typical aircraft wing construction was evaluated for the ailerons. It consisted of an aluminum skin, supported by a series of chordwise ribs and longitudinal stiffeners. The design was driven by fatigue and local skin buckling. Skin thickness of 0.1 in. to 0.2 in. were required. In this design the total aileron assembly weighed 4000 lb. per blade. It demonstrated the feasibility of the approach and provided a baseline to measure future designs. The final design and fabrication were to be performed by a vendor selected from competitive bids. The vendor would be free to use his own design and material system. Vendor candidates, experienced in structural compo-

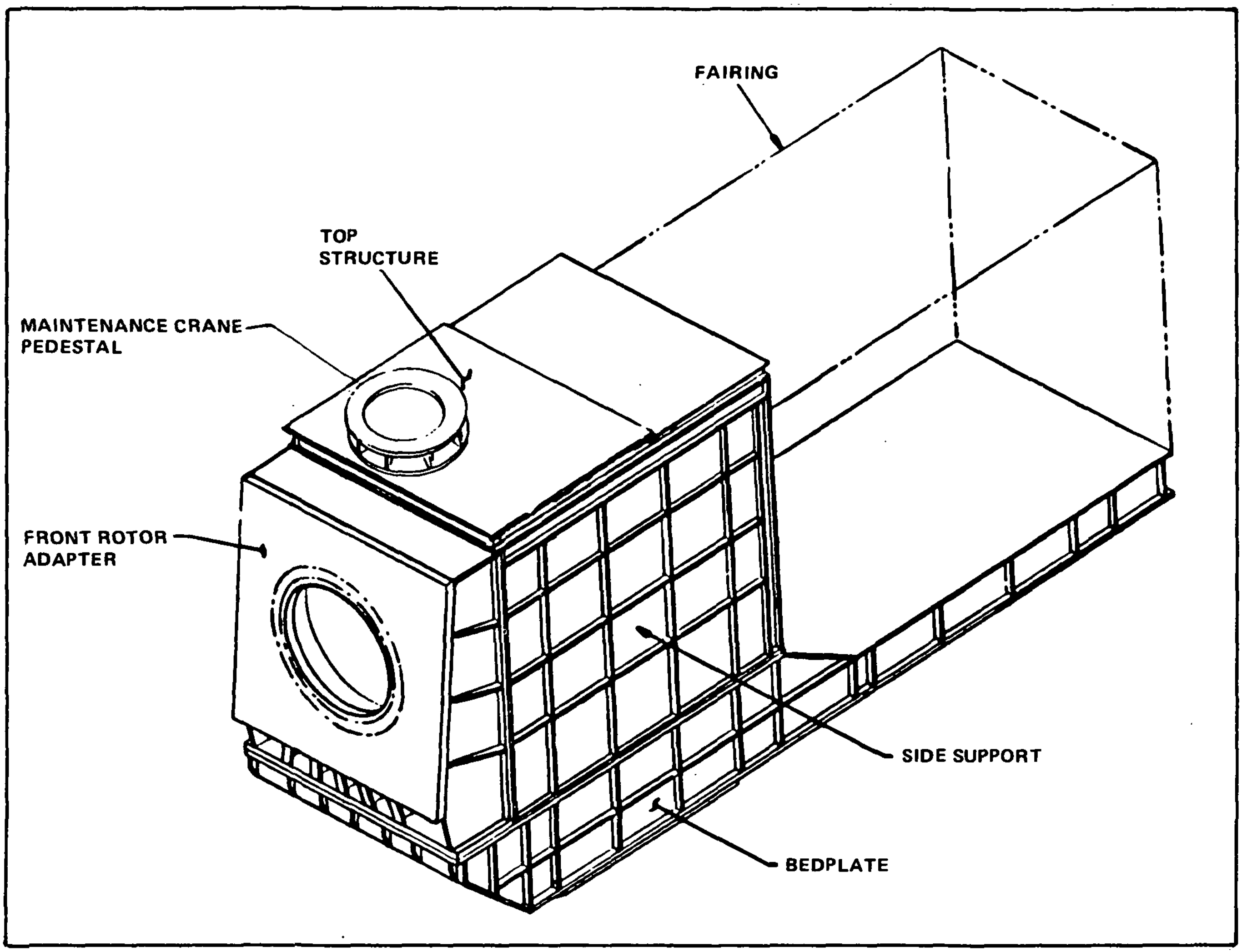

FIGURE 9. NACELLE STRUCTURAL ASSEMBLY

sites and/or airframe construction, were identified at the close of the program.

Yoke and Rotor Support

The yoke is a U-shaped structure welded from steel plates and a forged tube. It fits around the rotor at its center of rotation and supports it on elastomeric teeter bearings, in each "ear" of the yoke, as shown in Figure 8. Four teeter restrictors also connect the rotor and yoke. Each restrictor consists of a link attached on one end to the rotor, and engaged on the other end by two hydraulic caliper brakes mounted to the yoke.

The yoke rotates on two tapered roller bearings spaced 38 in. apart on the stationary spindle shaft as shown in Figure 3. The spindle is a 90 in. diameter rolled steel forging, having a 4.5 in. wall thickness. The spindle, which is bolted to the hub, supports the rotor weight and reacts all rotor loads except torque. A splined torque plate, bolted at its outer diameter to the yoke, transmits torque to the low speed shaft. A low speed brake, which is independent of the low speed shaft, is used to assist stopping the rotor. The disc of this brake is mounted to the outer yoke structure nearest the nacelle. The brake calipers are affixed to the nacelle.

DRIVETRAIN SUBSYSTEM

The drivetrain consists of a low speed shaft and gear couplings, a speed-increasing gearbox and

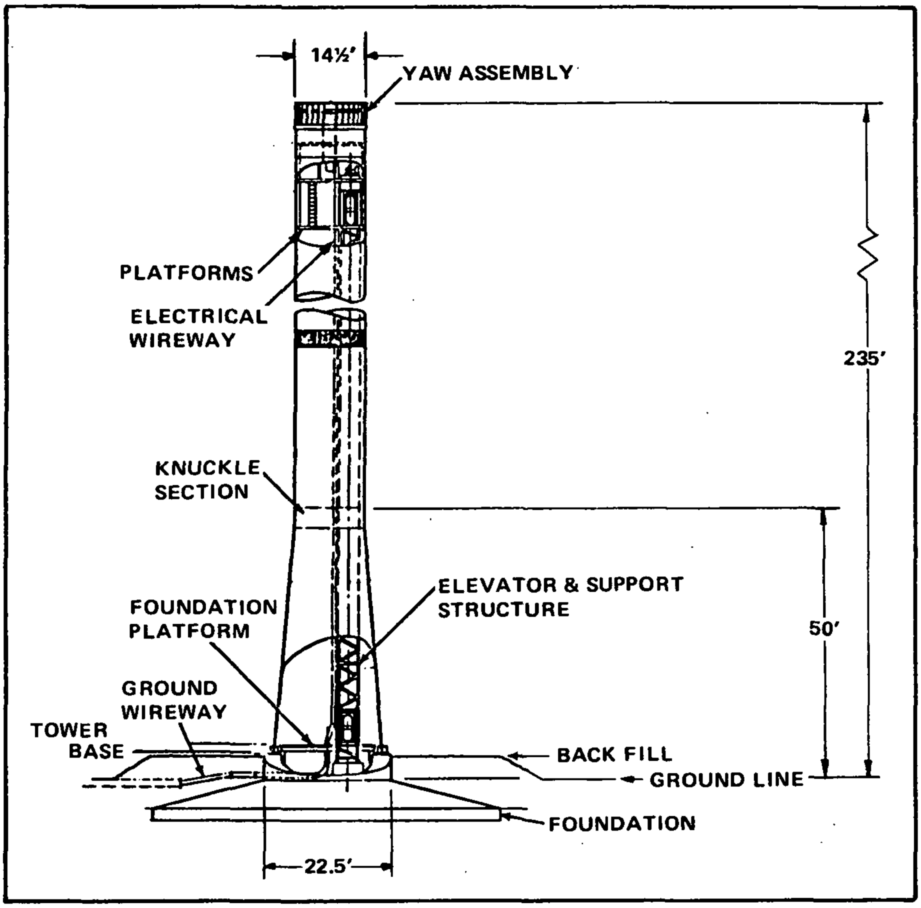

FIGURE 10. TOWER AND FOUNDATION

a high speed shaft with flexible couplings, as shown in Figure 3. The input speed varies between 13 and 17 rpm during normal operation. The rated input torque at the low speed shaft is 3.38 x 10^6 ft.-lb. The gearbox increases the speed so that the input to the generator varies between 1068 and 1396 rpm.

Low Speed Shaft and Couplings

The low speed shaft is a steel cylindrical forging, 132 in. in length. It has an outer diameter of 32 in. and an inner diameter of 10 in. Splined hubs are shrink-fitted to each end of the shaft. They mate with female splines on the yoke torque plate and in the gearbox.

Gearbox

The gearbox consists of three stages of speed increasers, with a total speed increase ratio of 82.14:1. The first two stages are epicyclic, while the high speed stage is a conventional parallel shaft design, consisting of a bull gear and pinion. The speed increaser includes an externally mounted reduction gear for rotating the rotor at 1 rpm. At 5 hp, electric motor can rotate the entire geartrain and rotor in either direction for the purpose of servicing rotor mounted components.

Philadelphia Gear Corporation supplied the gearbox design and was to manufacture the MOD-5A unit. They provided the gearbox for the earlier MOD-1 wind turbine.

NACELLE SUBSYSTEM

A cutaway view of the nacelle is shown in Figure 2. The nacelle provides structural support and environmental protection for all the components mounted within. It also has to react both static and dynamic rotor loads. The structural assem-

bly, shown in Figure 9, consists of welded steel plate and common structural shapes. The bedplate, which is the main structural member, is particularly stiff in bending, to limit the misalignment of the drivetrain under loading. The fairing is a standard commercial construction for lightweight commercial buildings, consisting of steel channel sections, covered with galvanized steel skins, inside and out.

Maintenance can be performed without a large external crane system, since a maintenance crane is mounted on the nacelle. Bolts, welds and wear can be inspected from the nacelle or yaw platforms. The nacelle design includes access to all rotating bearing seals, splined couplings and electronic gear.

Shipping size and weight requirements controlled design of major nacelle sections. The sections are bolted together in the field to form the overall structure. All exposed metal surfaces areas are painted in the factory with two coats of zinc rich primer. The finish paint coat and touchup paint are applied in the field.

TOWER AND YAW SUBSYSTEMS

The tower is a welded steel plate cylindrical shell with a conical base, as shown in Figure 10. It is assembled from 10 ft. high cylindrical sections which are joined by circumferential welds. Thicknesses of these sections vary between 0.7 and 1.6 in. Their total weight is 560,000 lbs. A 60 ksi yield strength steel was selected based on price, weldability, formability, toughness, and surface preparation. At a height of 50 ft., a formed piece, called the knuckle section, makes a transition between the cone and the cylinder. The tower is bolted to a reinforced concrete spread foundation. A circumferential base plate, ring and anchor bolt chairs form a transition between the base and the foundation. An elevator mounted inside the

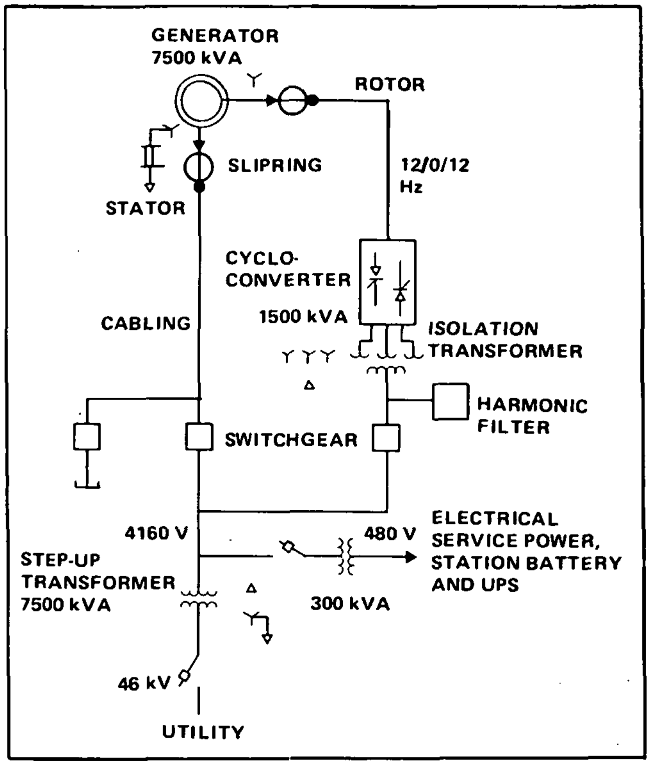

FIGURE 11. POWER GENERATION SUBSYSTEM

tower provides access to the nacelle. The yaw subsystem, internal platforms, emergency ladder and wireway and wire conduits are located in the tower.

The tower was designed to meet safe stress levels, and to provide the system with the proper dynamic frequencies. It is a soft tower design, with a fundamental bending frequency of 0.34 Hz. This frequency is between the one and two per revolution forcing frequencies of the blade. This frequency lowers the system fatigue loads, not only for the tower, but for the whole system. The system can be tuned by several parameters, such as height (the most sensitive parameter), rotor speed, conical base dimensions and the foundation stiffness.

The tower was to be fabricated and erected by the Chicago Bridge and Iron Company (CBI). They are experienced manufacturers of large water towers. CBI also provided the towers for the MOD-2 wind turbines.

The yaw subsystem consists of the upper and lower cylindrical yaw structures fixed to the nacelle and tower, respectively, the yaw bearing, and the yaw drive. The yaw bearing, located 5 ft. below the bedplate, connects the rotatable upper structure to the stationary lower structure. The bearing supports the weight on the nacelle and transmits all nacelle and rotor loads, except yaw torque, to the tower. A three-row, rolling element bearing was selected. This type bearing, which can withstand large overturning moments, is often used in large cranes, antennas, excavators and other machinery in which rotational speeds are low.

The yaw drive system is comprised of brake calipers attached to the rotatable upper structure which engage a disc fixed to the lower yaw structure. A constant yaw position is maintained by engaging brake calipers that are grounded to the upper structure. These brakes are disengaged during a yaw maneuver and a set of motive brakes are applied. The motive brakes are connected to the upper structure by linear hydraulic actuators. Discrete increments of yaw motion are obtained by extending and retracting the actuators. At the end of each increment, the holding brakes are reapplied and the process is repeated until the desired yaw orientation is reached. This type yaw drive operated successfully on the MOD-0A in Hawaii.

POWER GENERATION SUBSYSTEM

A variable speed generator system is used on the MOD-5A. It will deliver constant 60 Hz, output power between 67% and 100% of its maximum speed. In addition to delivering electrical power, the system performs the following important auxiliary functions.

- motors the rotor to 3.7 rpm during startup
- supplies drivetrain torsional damping
- provides rotor speed control below rated wind speed
- acts as drivetrain torque limiter above rated wind speed
- assists shutdown by supplying back torque

A schematic of the power generation system appears in Figure 11. The generator is a 7500 kVA, wound rotor, 6-pole machine, with a 6300 kVA stator, and 1500/0/1500 kVA rotor. The stator output frequency is maintained at 60Hz by a static cycloconverter and its associated controls. The stator and cycloconverter output is 4160 V. While singly excited, the generator provides motoring duty between 0 and 300 rpm to rotate the blades.

The cycloconverter controls the generator air gap torque and reactive power regulation. The cycloconverter and its controls are located in an enclosure near the base of the tower. Output power, service power, control signals, and data are transmitted between the rotating nacelle and the stationary tower by the slipring assembly in the yaw subsystem. Switchgear for stator short, stator tie, cycloconverter tie and associated relays are located in the enclosure with the cycloconverter.

The stepup transformer is the interface between the generator and cycloconverter and the utility interconnect. Filters suppress the harmonic frequencies of the cycloconverter. The electric service provides the power for lighting, heating, cooling, hydraulic supply, lubrication, and miscellaneous services. The station battery provides the power for shutdown of the electrical switch gear. This uninterruptible power supply provides power for the instrumentation and controls when utility power is interrupted, to facilitate shutdown and enable the wind turbine to start and continue operation when the utility power is restored.

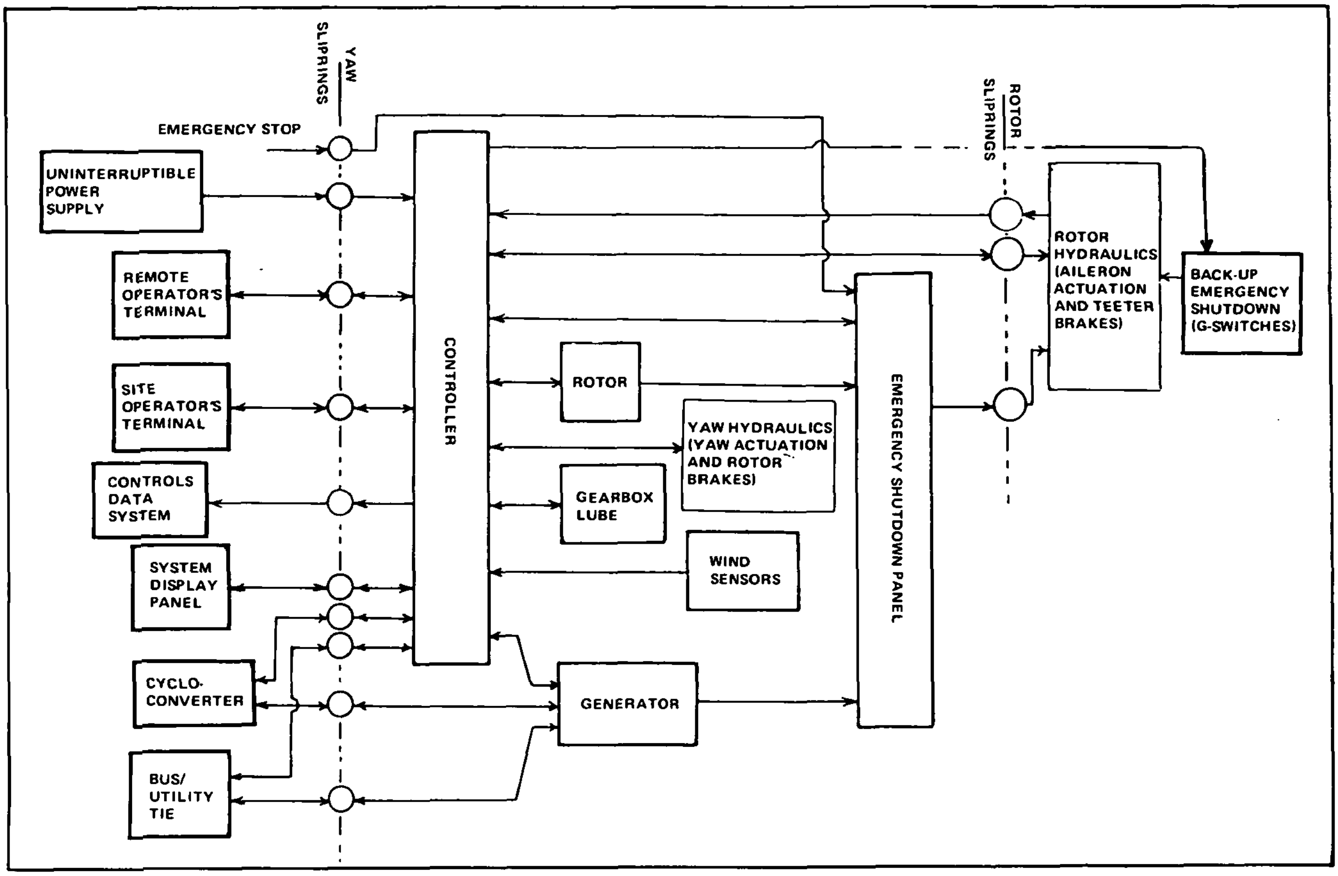

FIGURE 12. CONTROL SYSTEM BLOCK DIAGRAM

CONTROL AND INSTRUMENTATION SUBSYSTEMS

The elements and operation of the control and instrumentation subsystems are shown in Figure 12. The heart of the system is the controller. It is a dedicated, programmable digital computer having multiple input/output (I/O) ports. All control system algorithms and logic were coded into permanent memory. Necessary analog to digital (A/D) and D/A converters are built into the I/O modules. An EPTAC 700 series programmable controller was selected for this application. It is a modular, microprocessor-based system that uses the 8080A chip.

Commands from the operator and signals from the instrumentation system are the inputs to the controller. This data is processed by the controller and two forms of output are generated. One form is purely informational, in which operational data is fed in open-loop fashion to the system display panel, operator terminals, and controls data system. The second and more important form of output are commands to the active elements of the wind turbine namely, the:

- ailerons
- cycloconverter
- yaw drive
- teeter brakes
- rotor brake

For example, during power generating operation, the controller continually receives power, rotational speed, aileron position, and wind sensor signals. This data is analyzed on-line by the computer, using the programmed control system algorithms. Commands are sent to the

ailerons and cycloconverter to regulate rotor speed and torque, and to the yaw drive to maintain the proper wind alignment. Analogous procedures are followed during startup and shutdown.

The controller also continually monitors hydraulic pressures, temperatures, lubrication pumps, busbar connection, etc. for system faults. A normal shutdown is automatically implemented when an irregularity is sensed.

A second level of system protection is provided by the emergency shutdown panel. When critical sensors fail or exceed preset limits, the ailerons are feathered by hydraulic accumulators in the blades. The emergency shutdown panel is independent of the controller, and the normal operating aileron hydraulic system. It will initiate a shutdown in the event of a controller or power failure.

An engineering data system is included to evaluate the performance of the prototype MOD-5A. It records and processes structural, control, and electrical system data. It is compatible with the NASA data system used in past WTG programs.

The controller, signal conditioning, and the emergency shutdown panel are located in the nacelle in the controls equipment cabinet. The system display panel, operator's terminal, and the controls data subsystem are located in the office of the electrical equipment building at the base of the tower. Sensors are placed throughout the wind turbine system. Engineering data from the sensors are FM multiplexed over wires to the electrical equipment building. There are three multiplexers; one on the yoke, one in the nacelle, and one in the electrical equipment building. The units interface with a data van provided by NASA for recording data on magnetic tape and playback to a strip chart recorder.

NEW TECHNOLOGY

Several of the designs developed in the MOD-5A program have never been used in wind turbines. The MOD-5A was the first large wind turbine designed with ailerons for torque control and finger joints for joining wood blade sections at the site. The rotor support design was another innovation. The large rotor diameter and high power rating were also new in the wind turbine industry.

These unique features were subjected to extensive analyses and laboratory testing. For example, the ailerons were tested in two-dimensional wind tunnel tests, and in a three-dimensional, scaled test on NASA's MOD-0. Small finger joints were tested in the laboratory, to determine static and fatigue allowables, and the process for making and bonding the joints was demonstrated in a full-scale test. The design of the variable speed generator was based on similar applications for variable speed drives. The allowables for the laminated wood material were determined in an extensive development testing program, and size effects were determined in a series of tests that used specimens up to a 24 in. x 6 in. x 32 ft. in size.

DEVELOPMENT AND ANALYSIS OF THE DESIGN

CONFIGURATION OPTIMIZATION AND DEVELOPMENT

Table 4 traces the evolution of the MOD-5A design from the Proposal state at the start of the program through the Final Design. The Conceptual Design phase focused on configuration optimization. Wide ranges in system size and many different design variations were evaluated. The emphasis was placed on identifying a configuration with the lowest potential COE. The major outcome of the Conceptual Design was the selection of the 400 ft. diameter, upwind, wood rotor. The rating was increased to 5MW in concert with the new diameter. Understandably, this configuration still lacked the design detail needed for a workable system. Therefore, Preliminary Design focused on further evaluation, refinement, and development of this selection. Two significant configuration changes, noted in Table 4 were made during this period. The rating was increased to 7.3MW resulting in 10% more energy capture, and the continuous wood blade, which eliminated the steel to wood root-end joints, was adopted. During Final Design, a major emphasis was placed on reducing risk in the design. The non-rotating spindle support was introduced on the MOD-5A as a result of MOD-2 rotor shaft failures. The gearbox became correspondingly simpler, having to carry only torque loads. Finally, among other advantages, the variable speed generator provided flexibility to change operating speeds in the field to avoid load amplification caused by resonances.

Common elements of all the configurations shown in Table 4 were two-speed operation, a teetered rotor, tip speeds from 350-375 ft./sec., rotor solidity between 3% and 4%, and a tower height of approximately 250 ft. These parameters were also outcomes of the sizing and trade studies.

System Sizing Studies

The system size for minimum cost of energy was determined by systematically varying the

TABLE 4. EVOLUTION OF THE MOD-5A

	PROGRAM START 7/80	CONCEPTUAL DESIGN 3/81	PRELIMINARY DESIGN 4/82	FINAL DESIGN 11/83
ROTOR DIAMETER	350 FT	400 FT →	→	→
BLADE MATERIAL	FIBERGLASS	WOOD →	→	→
ROTOR ORIENTATION	DOWNWIND	UPWIND →	→	→
RATED POWER-KW	4000	5000	7300 →	→
ROTOR CENTER SECTION	STEEL INNER BLADE AND HUB-BOLTED TO FIBERGLASS	STEEL INNER BLADE AND HUB-STUDS TO WOOD	CONTINUOUS WOOD EXTERNAL STEEL YOKE →	→
ROTOR SUPPORT	LOW SPEED SHAFT TO GEARBOX →	→	→	NON-ROTATING SPINDLE TO NACELLE, STAND-ALONE GEARBOX
ROTOR TORQUE CONTROL	PARTIAL SPAN CONTROL →	→	→	AILERONS
GENERATOR	SYNCHRONOUS →	→	→	VARIABLE SPEED

quantities shown in Table 5. These sizing parameters enable the annual energy capture to be computed. The energy output is proportional to the rotor area, characterized by the diameter, and depends on the rating of the system. Rotor speed and solidity, taken together, establish the wind speed at which peak rotor efficiency occurs. For maximum energy capture, this wind speed should lie in a range that occurs most frequently over the year. Tower height also effects energy capture due to the increase in wind speed with altitude.

To complete the cost of energy calculations, the cost of each major subsystem was expressed as a function of one or more of the sizing parameters. For example, the gearbox cost which depends primarily on input torque, would be a function of rated power and rotor speed. The cost relationships were developed over the full ranges indicated in Table 5. After the initial optimization, the ranges were narrowed and point designs were established at 300, 350, 400, and 500 ft. rotor diameters. The cost relationships were then adjusted to reflect these more accurate values in the final evaluation. The optimization procedure was automated in GE's computer code, WINDOPT, which uses multi-variable scan and maximum slope techniques.

TABLE 5. SYSTEM SIZING PARAMETERS

PARAMETER	RANGE INVESTIGATED	FINAL VALUE
ROTOR DIAMETER	150-550 FT.	400 FT
RATED POWER, DEFINED BY POWER DENSITY	30-60 W/FT.^{2}	58 W/FT^2 (7.3 MW)
ROTOR SPEED, DEFINED BY TIP SPEED	250-450 FT./SEC.	352 FT/SEC.
ROTOR SOLIDITY, DEFINED BY EFFECTIVE BLADE AREA/DISC AREA	2.5-4.0%	4%
TOWER HEIGHT, DEFINED BY GROUND CLEARANCE	25-150 FT.	50 FT. (250 FT. HUB HEIGHT)

Results of the system sizing study, which are shown in Figure 13, indicated that a 400 ft. diameter rotor system had the lowest cost of energy. Therefore, this diameter, was selected at the end of Conceptual Design and frozen for the remainder of the program. Although there is latitude to fine-tune the other sizing parameters, a change in diameter will significantly affect all structural components.

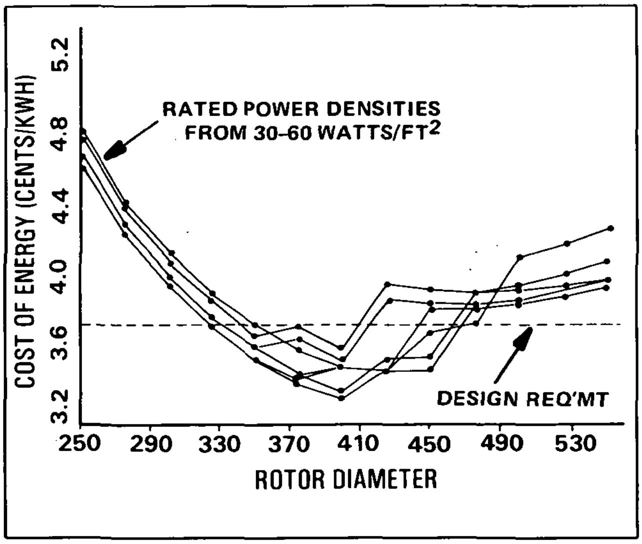

FIGURE 13. SIZING OPTIMIZATION RESULTS

The various curves in Figure 13 denote different rated powers. The optimum is 5MW, which was selected at the end of Conceptual Design. During Preliminary Design, however, detailed analysis indicated that the gearbox loading was lower than originally thought. Further load reduction was achieved by inserting a torque-limiting device in the drivetrain. Initially this was a slip-coupling on the high-speed shaft. Later the variable speed generator served this function. With the new loads, the existing gearbox design was underrated. Rather than designing a new, less-costly gearbox, the system was progressly uprated to 7.3MW. The small increase in cost to the electrical system

was more than offset by a 10% increase in energy capture. Furthermore, the higher rating was more appropriate to the higher wind speed site in Hawaii, where the first machine was to be built.

The tip speed, at the higher of the two rotor speeds, was set at 350 ft./sec. at completion of the sizing study in Conceptual Design. This was slightly below optimum for the then 3% solidity rotor, however it was thought to be a safe maximum for the wood blades. Further analysis permitted the tip speed to be raised to 375 ft./sec. during Preliminary Design. It was lowered back to 352 ft./sec. in Final Design, however, to provide improved performance with the wider chord blades adopted in the Final Design.

The blade root chord was increased from 200 in. to 300 in. during Final Design to lower inboard blade stresses. For a given load level, a wider chord promotes structural efficiency and reduces blade weight. Shipping and assembly considerations were the practical limits to chord width experienced with the MOD-5A. Two factors prompted the chord change. First, wood strength tests conducted during Preliminary Design produced a significant reduction in load allowables. Second, fatigue load predictions had increased. The increase stemmed from weight growth in the steel partial span control, and a more thorough understanding of wind turbulence effects, first applied to wind turbines during Preliminary Design. During Final Design when the ailerons replaced the heavy partial span control, the loads dropped and the chord could have been reduced. Instead, the lighter weight solution of reducing blade shell thickness was chosen. The solidity of the final wide chord rotor was 4% as noted in Table 5.

The sizing studies indicated that the cost of energy was relatively insensitive to ground clearance between 25 ft. and 60 ft., and the upper end of the clearance range provided the maximum design flexibility. Fifty ft. was selected as the ground clearance at the end of the Conceptual Design phase. During the Preliminary and Final Design phases, this selection was evaluated further, considering cost, maintenance, and frequency placement requirements. The ground clearance was reduced to 40 ft. during Preliminary Design. It was raised back to 50 ft. during the Final Design, to lower the tower stiffness so that the system's bending frequency requirements were satisfied.

Subsystem Trade-Off Studies

Eight major trade-off studies, summarized in Table 6, were conducted. This work began, and received greatest emphasis, in Conceptual Design. As more information became available in Preliminary and Final Design, the last four trade-offs in Table 6 received continued attention. Cost, reliability, complexity, and risk were evaluated in each study. The cost of energy was the major deciding factor in Conceptual Design. The other factors received increased emphasis during the later stages of the program.

Blade Material — Wood, steel and transverse filament tape (TFT) glass fiber composite were considered as blade materials. The objective was to determine which material would provide the lowest cost of energy for the entire wind turbine system. Thus, not only were the direct blade costs important, but blade weight was also significant, since it has to be supported by other system elements. Because the system size could influence the choice of blade material, and vice-versa, this trade-off was conducted in parallel with the system sizing optimization. This study was performed with three supporting subcontractors: Chicago Bridge and Iron (CBI) for the steel studies, Structural Composites, Inc. (SCI), for the TFT glass fiber studies, and

TABLE 6. SUMMARY OF MAJOR TRADE STUDIES

STUDY	ALTERNATES CONSIDERED	SELECTION	ATTRIBUTES
1. BLADE MATERIAL	• GLASS FIBER (EPOXY & POLYESTER) • STEEL • WOOD/EPOXY	• WOOD/EPOXY	• LIGHTEST WEIGHT • LOWEST COST
2. BLADE ARTICULATION	• INDEPENDENTLY CONED BLADES • TEETERED ROTOR	• TEETERED ROTOR	• ALLOWS UPWIND • MOST FAMILIAR DESIGN • LOWEST COST
3. WIND ORIENTATION	• UPWIND • DOWNWIND	• UPWIND	• LOWEST COST • LOWEST LOADS • LOWEST SOUND
4. NUMBER OF ROTOR SPEEDS	• ONE SPEED • TWO SPEED (UP TO 2:1)	• TWO SPEED 1.2:1 SPEED RATIO	• GREATER ENERGY CAPTURE • LOWER COE
5. TORQUE CONTROL	• AILERONS • PARTIAL SPAN CONTROL	• AILERONS	• LOWEST COST • LOWEST WEIGHT • CONTINUOUS WOOD BLADE
6. ROTOR SUPPORT/ GEARBOX	• SEPARATE ROTOR SUPPORT AND GEARBOX • ROTOR INTEGRATED GEARBOX	• SEPARATE ROTOR SUPPORT AND GEARBOX	• LEAST RISK • SIMPLIFIED GEARBOX DESIGN
7. ROTOR CENTER SECTION	• STEEL ATTACHED TO WOOD BLADE WITH STUDS • WOOD WITH EXTERNAL STEEL YOKE	• WOOD WITH EXTERNAL STEEL YOKE	• IMPROVED LOAD PATH • ELIMINATES WOOD/ STEEL JOINT
8. GENERATOR	• SYNCHRONOUS • VARIABLE SPEED	• VARIABLE SPEED	• ALLOWS FIELD TUNING • SIMPLIFIED DRIVE-TRAIN • STARTS AILERON ROTOR

Gougeon Brothers, Inc. (GBI) for the wood studies. They each supplied material properties data and costs estimates as a function of cross-sectional size.

Point designs were developed for each of the materials over a wide range of diameters and planform shapes. This was accomplished using the GE computer code, called SECTION. The code iteratively determines the blade cross-sectional skin thicknesses required for a given set of applied loads, blade external geometry, and material properties. Once the internal as well as external geometries are known, the code computes the blade weight and cost using the data furnished by the subcontractors. Literally hundreds of rotor configurations were evaluated for each material.

The results of this extensive study are shown in Figure 14. The cost and weight of rotors of each material are plotted against rotor diameter. The graph indicates that a wood rotor would weigh and cost the least for rotor diameters between 300 and 500 ft. Consequently, laminated wood/epoxy was chosen as the rotor material.

Blade Articulation — The teetered rotor was the baseline configuration for the MOD-5A.

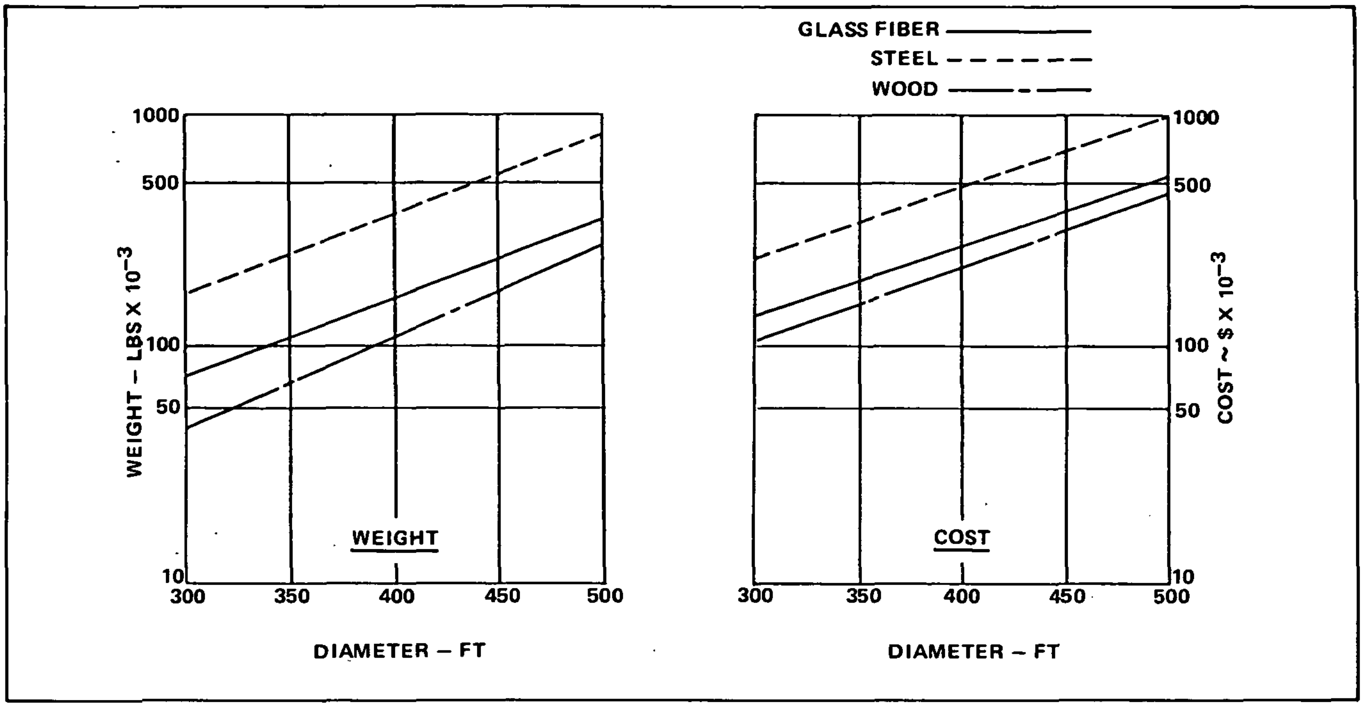

FIGURE 14. BLADE COST AND WEIGHT COMPARISON FOR GLASS FIBER, WOOD AND STEEL ROTORS

However, an independently coned configuration was also studied, because of its potential to reduce rotor loads. Rotor design loads were calculated for each configuration. Comparative weights and costs were derived from these design loads. Simultaneously, the performance and energy capture of each configuration were computed. The energy capture and cost data furnished the information required to calculate the cost of energy for the two configurations.

Substantially reduced loads on the independently coned rotor substantially reduced the rotor weight. On the other hand, the energy capture of the independently coned rotor was 2% less than that of the teetered rotor. The savings from the weight reduction were not enough to overcome this difference in energy capture. There were two other reasons for using the teetered rotor. The downwind, coned rotor generated much more noise than the upwind teetered rotor, and the teetered rotor was less of a risk because it had been extensively analyzed and tested on recent wind turbine generators.

Wind Orientation — The baseline proposal was for a teetered preconed rotor, downwind of the tower. As a result of analysis and technical direction from NASA-Lewis Research Center, the configuration was changed to an unconed rotor, upwind of the tower. The prime motivation for this change was to reduce rotor noise. Other advantages of the upwind configuration, which reduce weight and cost, are:

- reduced yaw bearing overturning moments because the rotor thrust now opposes the gravitational moment
- reduced rotor loads because tower aerodynamic interference is minimized
- a simpler hub design without precone

The disadvantage of the upwind configuration is the need for increased blade clearance. This was provided by tilting the rotor axis. The initial 9° tilt was reduced to 7° during Final Design.

Number of Rotor Speeds — The proposal baseline was a two-speed system. During Conceptual Design, energy capture calculations were made for one and two-speed systems operating at a site having the specified MOD-5A yearly wind speed distribution. The two-speed system, which operates near peak efficiency below rated wind speed, delivered 2 to 3% more energy than the best single speed system. Costs to implement two-speed operation were more than offset by the energy gain. Therefore, two-speeds remained in the baseline configuration. It was accomplished mechanically, using a two-speed gearbox until Final Design. Then, the introduction of the variable speed generator eliminated the cost and shifting losses associated with the two-speed gearbox. While this system could vary the rpm continuously, two discrete speed ranges were retained to avoid operation at structural resonances.

Torque Control — Blade torque control studies began early in the program. Costs for the torque control designs were compared to those of the baseline design for the partial span control system. The choice of blade material affected the choice of a torque control system significantly. During a trade-off study of torque control methods for the glass fiber blade, partial span control was compared with aileron control. The aileron system cost less than partial span control, but in other respects, the aileron system was inferior to partial span control.

Ailerons were less effective at low rotor speeds, and the rotor would have to be started with a motor. The aileron system also had more components than partial span control. The concept was rejected since its cost advantages could not offset the disadvantages.

However, as the design progressed, problems with the partial span control system on the wood blade were encountered. The joints between the steel partial span control and the wood blade were a problem. The weight of the partial span control increased too much, increasing loads on the blade, and decreasing the elastic bending frequency of the blade.

Alternative control systems were reevaluated. These studies indicated that ailerons would reduce costs and weight, avoid complex joints between wood and steel, and provide better blade frequency placement. The variable speed generator, now in the system, could be used for startup. Furthermore, recent aerodynamic test data supporting ailerons had become available. During the Final Design phase, the torque control method was changed to ailerons.

Rotor Support/Gearbox — The MOD-5A baseline had a rotor-integrated gearbox until the Final Design phase. In this configuration, the low-speed shaft was used to both support the rotor and transmit torque to the gearbox. The shaft ran from the rotor to a large mono-bearing at the input end of the gearbox. The gearbox housing was designed to withstand the rotor loads which were transmitted through the bearing. During Conceptual Design this configuration was compared against one in which the rotor was supported by the nacelle structure and torque only was transmitted to a conventional gearbox. The rotor-integrated gearbox was determined to have the lowest cost.

As the design progressed, the rotor-integrated gearbox became more expensive and more complex than early estimates had predicated. The load carrying function placed additional, unaccustomed burdens on the gearbox manufacturer. The failure of the MOD-2 low-speed shafts prompted the search for an alternate arrangement that would reduce risk on the MOD-5A. The solution was to support the rotor

by a non-rotating spindle located as close as practicable to the rotor center. Torque only was transmitted by a much smaller low speed shaft to a stand-alone gearbox in the final system.

Rotor Center Section — At the end of Conceptual Design the rotor had a steel center section which interfaced with the wood blades at 8.5% radius. The low-speed shaft penetrated the steel section and was attached to internal teeter bearings. The blades were attached to the steel section using steel studs imbedded into the wood cross-section. While steel to wood stud joints were used successfully on the smaller MOD-0A machine, there were problems in developing enough joint strength on the much larger MOD-5A. Analyses conducted during Preliminary Design, led to a continuous wood center section supported by an external steel yoke. *The center section was bonded to the* outer blade sections at finger-shaped joints. This wood to wood interface has a high joint efficiency. The continuous wood structure and external support provided load paths superior to the earlier configuration. Although neither design was fully mature at this point, cost and weight estimates favored the final configuration.

Generator — Trade-off studies between a variable speed generator and a synchronous generator with a two-speed gearbox were conducted during Conceptual and Preliminary Design. The synchronous system was initially chosen because it provided lower cost of energy. While this conclusion is probably still true, the variable speed system was adopted in Final Design because its benefits outweigh the small cost differences. Operating speeds may be changed in the field to detune a resonance or maximize energy capture at sites having different wind characteristics. The inherent damping characteristics of the system eliminated the need for a special gearbox suspension system previously used to provide drivetrain damping. The torque-limiting, slip-coupling was no longer needed on the high speed shaft and the gearbox became a single-speed unit. Rotor dynamic loads were reduced during normal shutdowns because aileron feather rate requirements could be lowered by using the generator to supply a retarding torque. Finally, the system is ideally suited for the aileron blades because it can double as a motor during startup. Several types of variable speed systems were investigated. The final trade-off was between a static Scherbius (Scherbiustat) and Load Commutated Inverter (LCI) drive system. The Scherbiustat variable speed system was selected because it had the lower cost.

DEVELOPMENT TESTS

A significant amount of development testing was performed to reduce program and design risk and to establish a technology base for the newer, innovative features of the MOD-5A system. Tests were conducted in three general areas:

- wood material tests — to support the rotor design
- aerodynamic tests — to support the airfoil and aileron development
- controller checkout

Wood Material Tests

The blade design commenced using material properties taken from the MOD-0A wood blade program and the extensive data base compiled by Forest Products Laboratory (FPL). The FPL data were derived, for the most part, from tests of small, clear wood samples. Sufficient data for the laminated, plywood-based veneer construction proposed for the MOD-5A blade

did not exist. Costs would be prohibitive to conduct extensive material characterization tests on these veneers. Therefore, selected tests were designed to calibrate the laminated veneer properties to the large, existing FPL data base. In this way few samples could be tested, and secondary, less important properties could be derived from the data base. Additional tests were designed to validate the blade joints and bolsters. GE worked with Gougeon Brothers, Inc. (GBI) in performing the wood tests, which are summarized below.

Phase A Static Tests — The Phase A test evaluated the static properties of the composite of Douglas fir veneer and GBI's West System® epoxy used in the blade. The laminated veneer samples had strength properties comparable to those reported by FPL for small, clear samples.

Phase B Fatigue Strength Tests — The Phase B test evaluated the fatigue strength of the Douglas fir and West System® epoxy composite. Cyclic loading capabilities were determined, to supplement the static strength data compiled in Phase A. Specimens were made from two categories of veneer, which were determined by the longitudinal Young's modulus. All testing was conducted parallel to the grain and compared the two veneer grades in various load ratio tests. The effect of moisture content on fatigue strength was monitored by measuring each specimen for moisture content. Fatigue allowables, comparable in magnitude to the FPL data, were derived from the test.

Filled Epoxy Test Program — Epoxy is the adhesive and filler material for bonding the Douglas fir laminae. Thixotropic epoxy was used as a void filler, a filler material and as an adhesive for bonding metal parts to wood. The testing determined the properties of asbestos-filled and carbon-filled West System® epoxies. Strength and fatigue capabilities and thermal properties were needed for applications throughout the blade. Based on the test results, the asbestos-filled epoxy was chosen. However, federal safety regulations pertaining to the use of asbestos became too stringent to allow the asbestos filler to be used. Consequently, a second carbon-filled epoxy, which GBI had previously tested for use on large surface areas, replaced the asbestos-filled epoxy.

Scarf Joint Testing — In commercially available wood veneer products, two types of joints at veneer ends are common. The ends are either overlapped, or butt joints are used. GBI's blade production process was not compatible with overlapping joints. Therefore, butt joints were used in GBI's previous applications and early in the MOD-5A program. However, butt joints can cause problems. They usually result in small gaps at the joint. Sometimes the epoxy does not fully seal the gap, and the gap interrupts the continuity of the wood fiber. Previous tests indicated that butt joints reduce the strength of members. As an alternative to the butt joint, GBI developed a method of scarfing sheet ends that results in a joint that transfers a load across the angled glue line without breaking continuity. These scarf joints could be made at negligible extra cost by slightly modifying the veneer trimming process.

Static and fatigue tests were made to compare the strengths of the butt and scarf joints. The scarf joints were more than 5% stronger and consequently they were selected for the MOD-5A design.

Moisture Effects Testing — The available fatigue data on wood did not provide enough information to determine the effects of moisture on fatigue life. This program tested the effects of moisture on the fatigue characteristics of

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Douglas fir veneer and West System® epoxy, for forces parallel to the grain of the laminae. Fatigue data, under fully reversing loads and at various load ratios in tension/tension and compression/compression fatigue, was obtained. The data was used to establish design allowables for a range of moistures.

Size Effect Testing — Size effect is the premise that the larger the stressed volume of material, the higher the probability that it will contain a critical flaw. Since the MOD-5A blade is very large, size effect was addressed both theoretically and by test. Static test specimens 1/2 ft. x 2 ft. x 24 ft. were loaded in tension until failure. Figure 15 shows one of these wood-laminate specimens under load in the test facility at Lehigh University. Fatigue tests were conducted at the University of Washington. Thirty foot long specimens, having 1 1/2 in. x 8 in., 2 in. x 8 in., and 3 in. x 8 in. cross-sections, were used. The size effect testing led to a 30% reduction in the blade allowables.

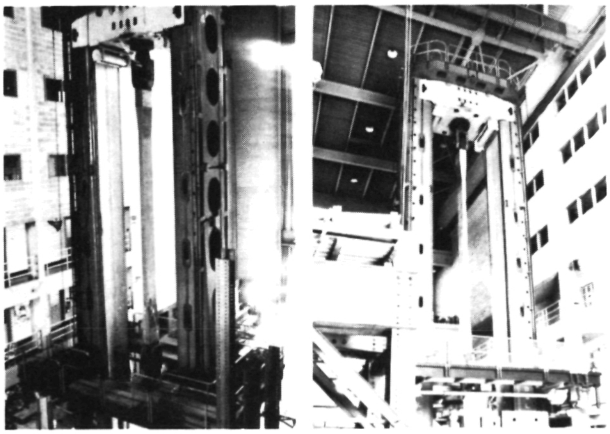

FIGURE 15. WOOD SIZE EFFECT STRENGTH TESTING

Finger Joints — The finger joints, used to bond the five MOD-5A blade sections together in the field, are new to wind turbine technology. Considerable testing was done to develop and validate their design. First, static tests provided data on joint strength, as a function of finger length, finger angle, bond gap thickness, and glass fiber or Kelvar augmentation of the laminae. The test specimens were 1 1/2 in. thick laminates having a single finger of full-scale dimensions. Next, specimens of the best configuration were constructed and fatigue tested. The static and fatigue tests indicated a joint efficiency from 88-92%. The blades are thickened in the joint areas to achieve strengths consistent with the rest of the blade. Questions still remained as to whether a complete finger joint could be accurately fabricated and assembled. Therefore, full-size blade sections having finger joints were made. Figure 16 shows these field-joint sections being transported and rigged for trial fitup before the actual

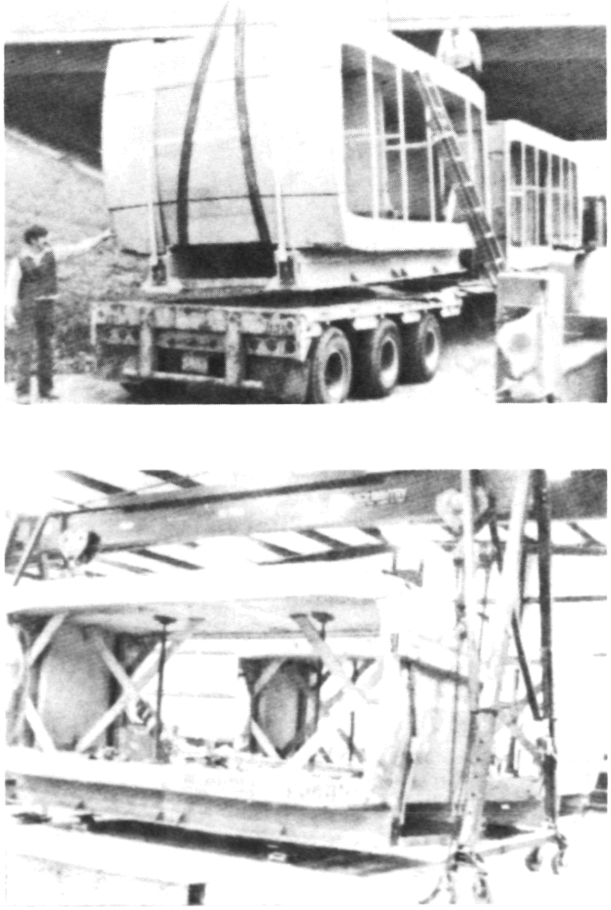

FIGURE 16. SHIPPING AND TRIAL FIT OF THE FIELD JOINT PROCESS DEMONSTRATION UNIT

bonding. Dimensional accuracy was demonstrated. Photographs of the finish joint, which was bonded using a filled epoxy adhesive, appear in Figure 17. After curing, the field-joint process demonstration unit was disected to provide test samples from various locations around the joint. These were static load tested and the strengths were comparable to those found with the earlier single finger specimens. The fatigue strength of a complete finger joint

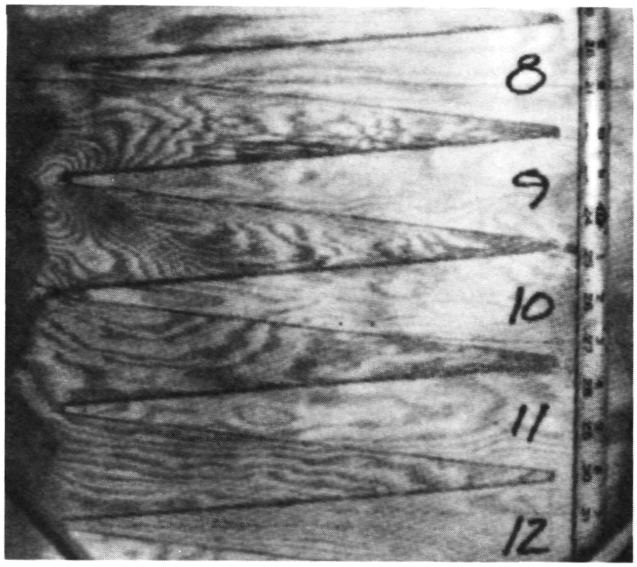

FIGURE 17. VIEW OF THE FINISHED JOINTS OF THE FIELD JOINT PROCESS DEMONSTRATION UNIT

has not yet been verified. NASA conducted a preliminary fatigue test of a cantilever box beam containing a finger joint, which resulted in a premature failure through the joint. Further research on the characteristics of this type of joint is required.

Longitudinal Bonded Joints — This test provided data on the durability of longitudinal bonded joints in the Douglas fir veneer and West System® epoxy. Test specimens were subjected to static and fatigue loads in bending tests. The test studied the influence of defects in the bond line of the joint, and of high and low temperatures on the joint.

Blade Teeter Area — This series of tests was used to evaluate the bolster laminates, their bond to the blade, and the fittings imbedded within the bolster. Eight scaled models were static and fatigue tested at various temperatures. Strain gauges were installed at critical locations to validate the finite element analyses. The glass fiber augmented, wood laminates were found satisfactory. The blade bond tests prompted a re-design of the spanwise taper at the ends of the bolsters. It was changed from a linear to a quadratic taper. The epoxy bushings that hold the teeter bearing cup and the fitting to the teeter brake rod were found satisfactory.

Aerodynamic Tests

Airfoil Development — The NACA 64-XXX airfoil family was selected for the MOD-5A. The airfoil thickness varies from 15% chord at the tip to 29% chord at the root. The relatively thick root-end sections are commonly required in wind turbine designs for structural strength. Published airfoil characteristics for the 64-XXX series however, do not go beyond a 21% thick section. Therefore, a wind tunnel test program was implemented to determine the aerodynamic characteristics of the thicker sections. The tests were conducted at full-scale Reynolds number at the Ohio State University Transonic Airfoil facility. The test program also investigated modifications to the thick sections that could enhance performance. Reductions in profile drag were derived with a raised, thickened trailing edge. This geometry was incorporated into the MOD-5A design.

Aileron Development — Aileron control of the MOD-5A wind turbine was a new application of an old technology. There was a large data base for ailerons, but no data was available for thick airfoils, or for the high angles of attack and high aileron deflections needed for the wind

turbine application. Wind tunnel tests were conducted to supply this data and to determine the aileron configuration. A plain aileron, hinged at 62% of chord, was selected. The data enabled the wind turbine operation with ailerons to be computed.

The aerodynamic performance predictions were verified by testing a rotor with ailerons on the NASA MOD-0 wind turbine in Sandusky, Ohio. The test facility and configuration are shown in Figure 18. Months of testing were conducted under various wind conditions. The test demonstrated that ailerons can effectively regulate rotor speed and torque, and limit overspeed to acceptable levels. Although the ailerons could not completely stop the rotor, they were able to bring it to a safe, low rpm from which a light-duty rotor brake could complete the shutdown.

FIGURE 18. AILERON TESTING ON THE MOD-0 WIND TURBINE IN SUPPORT OF THE MOD-5A

Controller Checkout

The controller hardware and software were checked out using a hybrid-computer based simulator of the wind turbine. The simulator received command signals output by the controller, such as aileron deflection, and computed the generator and rotor dynamic response. Simulated sensor measurements, based on this response, were in turn fed back to the controller. Wind speed and wind direction inputs to the simulator were arbitrary functions of time. The algorithms coded into the controller were thoroughly checked-out over the full range of expected wind turbine operation. The controller accumulated 2000 hrs. on the simulator with only one failure. This was an infant mortality of one of the output ports. In production, a complete check and burn-in test would be performed. This test would detect any failures of the type encountered.

SYSTEM DYNAMICS ANALYSIS

The objective of the system dynamics analysis were:

- to place the system's natural frequencies so as to avoid resonances
- to ensure aeroelastic stability
- to provide satisfactory control system performance

Natural Frequencies

The calculation of the system's natural frequencies used state-of-the-art finite element and modal synthesis techniques. The resulting natural modes were for the fully-coupled system. The analysis has shown the MOD-5A to be free of operational resonances. An unanticipated resonance could be detuned in the field by changing the operating speed with the variable speed generator. Resonant crossings during startup and shutdown were also analyzed. Load levels were all acceptable.

Aeroelastic Stability

The initial assessment of aeroelastic stability was made before the ailerons were incorporated. This analysis was performed using a computer code called GETSTAB, which GE developed during the MOD-1 program. The code analyzes both blade and coupled rotor-tower stability. Although many types of instability are possible, none were encountered in this first

assessment of the MOD-5A. These results are consistent with wind turbine experience. All the large wind turbines built under the DOE/NASA programs have been aeroelastically stable.

Since the use of ailerons was new in the design of large wind turbines, careful attention had to be applied to the aeroelastic stability of this system. A coupled blade-aileron flutter analysis was developed and coded into a new computer program called AILSTAB. The analysis showed that the MOD-5A blade and aileron system can be stabilized for all operating environments by either providing a sufficiently high impedance about the aileron hinge axis, or by mass-balancing the ailerons. The basic actuator system provides the necessary impedance during normal operation. To protect the system if an actuator fails, torsional dampers were installed, rather than mass-balancing the ailerons. These dampers are passive elements that will always be operative. The damper forces are well below the aerodynamic forces encountered during normal operation, so that their presence does not penalize the actuator design.

Control System

From the standpoint of dynamics, the key function of the control system is speed control. A rotor speed control loop and a generator speed control loop are used, as shown in Figure 19. The variable speed generator subsystem regulates generator air gap torque and the ailerons regulate rotor torque to provide speed control. Either a low speed or a high speed operating region is automatically selected for the most efficient use of the wind and the rotor.

At lower wind speeds the region varies between 13.2 and 13.8 rpm, while at higher wind speeds the range is from 16.2 to 16.8 rpm. The speed reference for the generator control loop is set at the lower end of the range - either 13.2 or 16.2. The generator airgap torque is set proportional to the difference between the actual rotor speed and the reference speed. A full-range speed error of .6 rpm corresponds

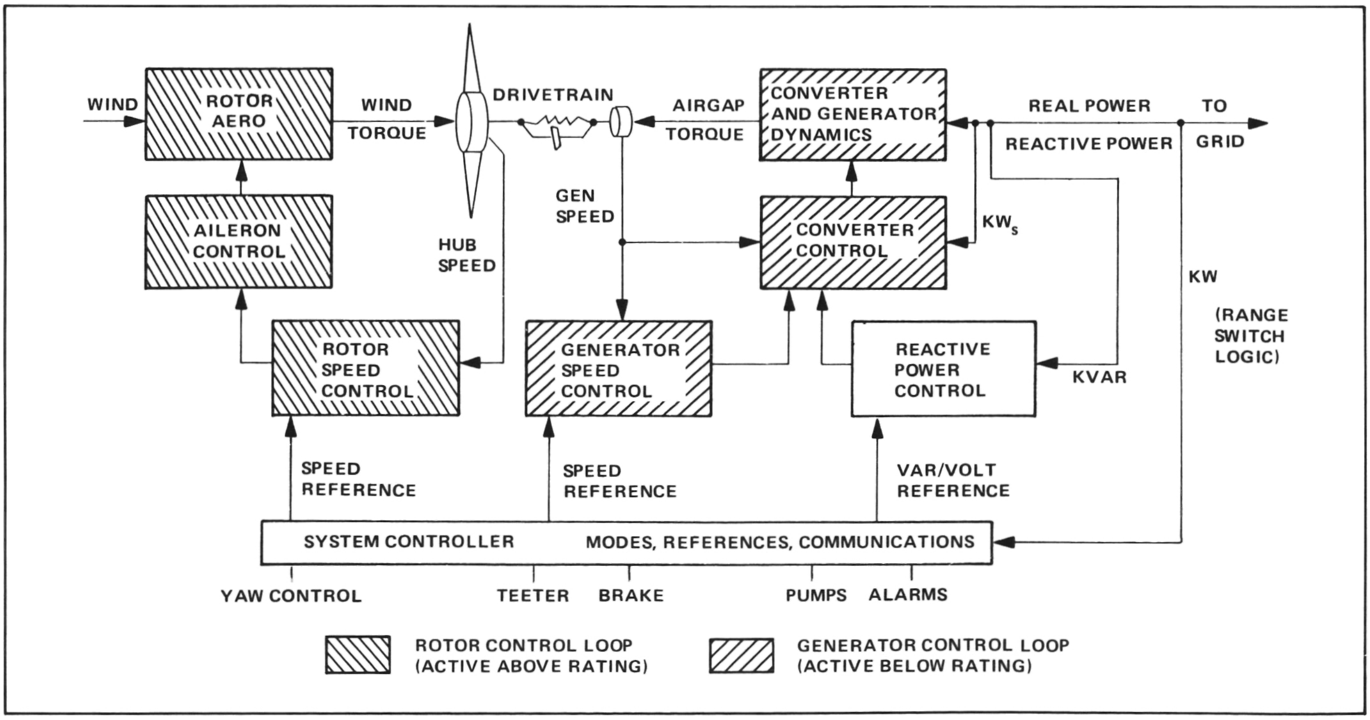

FIGURE 19. CONTROL SYSTEM DYNAMICS SCHEMATIC

to rated torque. Thus, the generator keeps the rpm within the desired range below rated wind speed. The speed reference of the rotor control loop is set at the upper end of the rpm range - either 13.8 or 16.8. Below rated wind speed, the rotor control loop in its attempt to attain its reference speed, drives the ailerons to the full power position in line with the blades. The ailerons will remain in this position during normal sub-rated operation. Above rated wind speed, the rotor control loop regulates the aileron positions to maintain 16.8 rpm, while the generator airgap torque is limited to 1.1 times rated. In this way, the ailerons are the active control element above rated wind speed and the generator is the active element below rated wind speed. Negligible interaction between the two speed control loops occurs because of a wide difference in bandwidth.

An important consideration in the control system design was its potential interaction with the wind turbine structure. Early testing of the MOD-2, the first large wind turbine with a soft low frequency tower, was plagued by undesirable coupling between the control system and the tower. To investigate these potential problems on the MOD-5A, the control system dynamics were incorporated in the GE aeroelastic load analysis code — TRAC. The code was able to simulate the interaction of the tower and control system that was experienced on the MOD-2. The MOD-5A control system was designed and shown by analysis to be free of these problems.

SYSTEM LOADS AND STRESS ANALYSIS

Significant advances in wind turbine loads analysis were made during the MOD-5A program. An improved aeroelastic loads prediction code, TRAC, was developed to analyze both transient and steady-state conditions. The code is a fully-coupled, non-linear analysis which contains all essential rotor, tower, and control system degrees of freedom. Key data and understanding, needed to model wind variations, were provided through the coordinated efforts of NASA and Battele-Pacific Northwest Laboratory. From these, wind models were developed to quantify mean-wind variations, large rotor enveloping gusts, and small-scale turbulence encountered by the rotating blades. Statistical methods were developed to combine the loads from each of these sources into common life-cycle histograms. Correlations with MOD-1 and MOD-2 test data verified both the load prediction and wind modelling techniques.

Design loads were calculated at major system interface locations. These include: eleven spanwise positions along the blade, the teeter bearings, the rotor support to nacelle interface, the yaw bearing, and four elevations along the tower. A complete set of shears and moments were supplied at each interface. These loads, in turn, were applied to detailed finite element models of each of the system's major substructures. An example is the yoke finite element model shown in Figure 20.

Both fatigue and limit loads were provided for each interface. The fatigue loads were specified in the form of histograms for the 30 year life of the machine. Typical probability distributions, derived from the load histograms, are shown in Figure 21. The curves apply to blade fatigue flapwise bending moments, which have been normalized by the mean bending moment at rated wind speed. Test data taken from MOD-2 operation is included for comparison. The stress analysis used the histogram data to insure a 30 year life. Various different life criteria were used depending upon the material and construction of the component.

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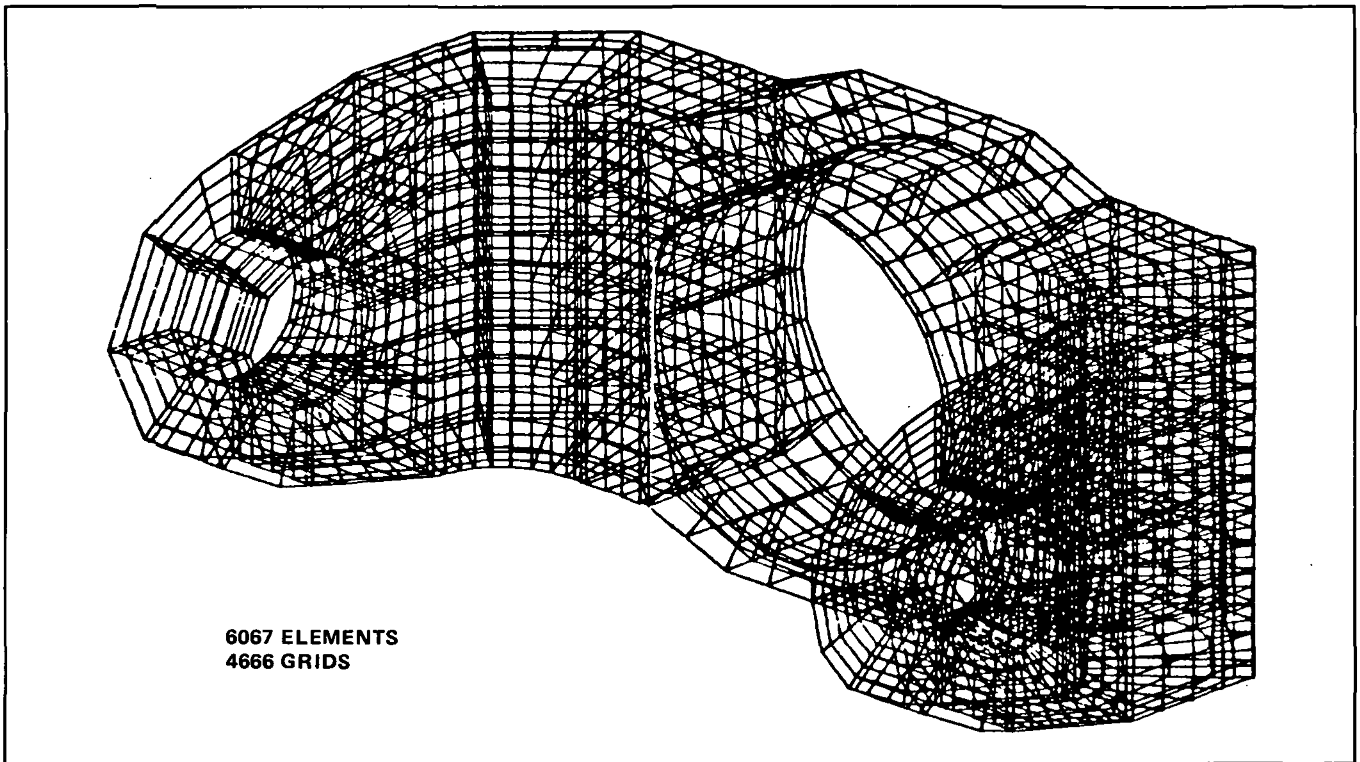

FIGURE 20. YOKE FINITE ELEMENT MODEL

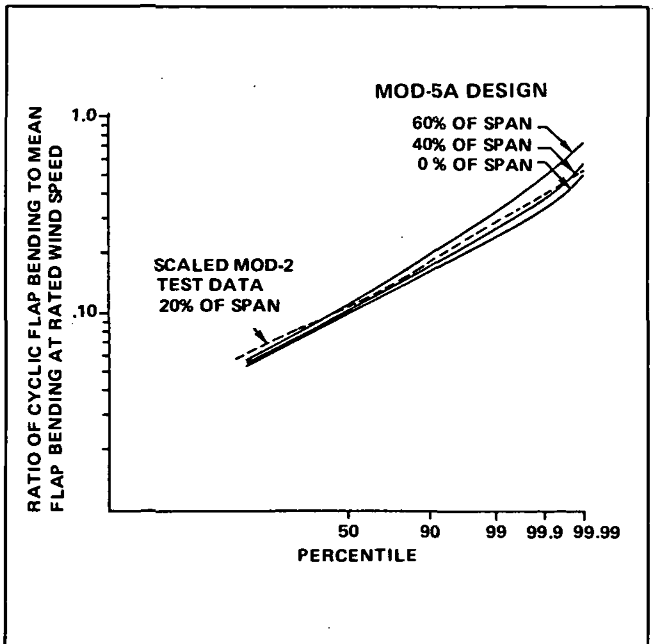

FIGURE 21. BLADE FLAPWISE BENDING MOMENT PROBABILITY DISTRIBUTIONS

Table 7 contains a summary of critical operating conditions used to compute the limit loads. Stress analyses were performed with these loads to check for yield and buckling. The system was designed to withstand the first four conditions without damage. The last case represents an unexpected extreme condition, which the MOD-5A could withstand without catastrophic failure. The design loads used in the fatigue and limit stress analysis were 15 to 25% greater than the predicted loads. Additional conservative measures were taken in defining the material allowable stresses, particularly in the case of the wood blades.

RELIABILITY, AVAILABILITY AND MAINTAINABILITY

Utilities emphasize the reliability and availability of power generation equipment, since unplanned shutdowns result in lost revenue. Reliability is defined as the probability that a

component or subsystem will perform its function. The design goal was to optimize reliability and maintainability to achieve maximum availability.

The reliability, availability, and maintainability of the major components of the wind turbine were analyzed. The results appear in Table 8. The availability projections for the 100th unit in a clustered installation were compared with the availabilities of other power generating systems, as shown in Table 9. Low head hydro was selected by the user's review board for these comparisons, because both systems depend on a renewable and varying energy source, and do not involve combustion. The projections for the MOD-5A match favorably.

TABLE 7. CRITICAL LIMIT LOAD CONDITIONS

	CONDITION	COMMENTS
1.	HURRICANE (130 MPH AT HUB)	TOWER BENDING AND FOUNDATION CRITICAL
2.	CONTROL HARDWARE FAILURE (60 MPH, 0° AILERON ANGLE)	INBOARD BLADE/ROTOR CRITICAL
3.	99.99TH PERCENTILE GUST AT RATED WIND SPEED, 25% OVER-SPEED, DESYNCHRONIZATION AND SHUTDOWN	OUTBOARD BLADE CRITICAL
4.	SHUTDOWN AT CUT-OUT WIND SPEED WITH YAW ERROR	SETS DESIGN REQUIREMENTS FOR TEETER BRAKES
5.	50% OVERSPEED, HIGH WIND ADVERSE AILERON SETTING	SURVIVAL CONDITION, SYSTEM DESIGNED TO PREVENT CATASTROPHIC FAILURE

TABLE 8. AVAILABILITY ANALYSIS FOR MATURE MOD-5A

	FAILURES/ YEAR	MEAN TIME BETWEEN FAILURES (HRS)	MEAN TIME TO REPAIR (HRS)	UNSCHEDULED DOWNTIME (HRS)	AVAILABILITY (%)
ROTOR SYSTEM	1	6,490	46	52	99.50
DRIVETRAIN SYSTEM	1	13,270	38	25	99.71
HYDRAULIC SYSTEM	3	3,074	15	43	99.51
POWER GENERATION SYSTEM	3	3,197	10	28	99.68
CONTROL AND INSTRUMENTATION SYSTEM	4	1,973	6	25	99.71
NACELLE, TOWER, SITE SYSTEMS	0.1	62,570	115	16	99.82
UNSCHEDULED DOWNTIME	12	732	16	189	97.84
SCHEDULED DOWNTIME (30 YR AVG.)				151	98.27
TOTAL				340	96.12

TABLE 9. RELIABILITY AND AVAILABILITY COMPARISONS (OPERATIONAL EXPERIENCE – REF: NERC 1970-79)

ANNUAL AVERAGES FOR MATURE DESIGNS					
ITEM	MOD-5A 100TH UNIT CLUSTERED INSTALLATION	LOW HEAD HYDRO	DIESEL	FOSSIL	GAS TURBINE
MEAN TIME BETWEEN FAILURES	732	8946	1044	897	872
AVAILABILITY %	96	94	95	83	86
TOTAL DOWNTIME – HOURS/YEAR	279	493	481	1504	1187
UNSCHEDULED	189	193	447	781	907
SCHEDULED	151	300	34	723	282
FAILURES PER YEAR	12	1	8	10	10
MEAN TIME TO REPAIR – HOURS	16	197	54	81	93

QUALITY ASSURANCE AND SAFETY

A comprehensive quality assurance and safety program was established to ensure that the hardware fulfilled all requirements imposed by NASA, GE and the utility which purchases the wind turbine. Three documents were developed: the MOD-5A Quality Assurance Plan, the MOD-5A System Safety Plan, and the MOD-5A Configuration Control Plan. The Quality Assurance Plan describes the procedures for procuring, examining, accepting and storing raw materials and purchased components. The System Safety Plan outlines the responsibilities of personnel on the program, lists the controls on the program and the controls on testing programs and test and assembly facilities. The Configuration Control Plan describes the procedure for controlling drawings and specifications generated for the MOD-5A wind turbine.

FABRICATION

GE's manufacturing plan for the wind turbine generator consisted of three parts: fabrication, factory integration and site assembly. Conventional manufacturing and fabrication methods were used in this plan. The yaw, nacelle, yoke and tower structures would be made in conventional shops. Specialty vendors were chosen to manufacture the gearbox, generator and bearings. The fabrication of the wooden blade consists of molding and machining the center, inboard and outboard sections. A vendor that specializes in wood products was chosen to make the blade.

FACTORY INTEGRATION

To ensure that all components fit and operate properly at the site, the important parts are assembled for a trial fitting in the factory. These parts include the yaw subsystem, nacelle, yoke and spindle assembly, gearbox, generator and other electrical and mechanical drive components. Then the equipment is disassembled, packed and shipped to the site.

SHIPPING

The following is the shipping plan developed for an installation at a site near Kahuku, Oahu, HI. Many components are shipped to an assembly area near King of Prussia, PA, where they are fitted, assembled and tested. The assemblies are divided into modules, which are shipped to a staging area on the west coast, in Portland, OR or Oakland, CA. The modules are loaded on ocean barges and shipped to Honolulu, HI. Subsystems and components that are not available or are not required for fitting, assembly, and testing in the factory are shipped directly to the staging area. Shipments are received at Honolulu, and are stored and transported to the site as required.

Three shipping modes — truck, rail and ocean — take into account the location of the supplier, the destination of the component, the size and weight of the material, the transit time and the shipping cost.

ASSEMBLY AT THE SITE

After the site has been prepared by grading, road construction, and the preparation of assembly and storage areas, the reinforced concrete foundation is constructed and prepared for the erection of the tower.

The tower parts are shipped to the site, and conventional equipment is used to weld them into cylinders. The tower is erected section by section, and welded into a continuous structure. When the tower is erected, the yaw subsystem is raised and welded in place. The nacelle

assembly is raised and bolted to the upper yaw structure. The gearbox, yoke and spindle assembly, high speed shaft, generator, and fairing are installed.

The laminated wood blade arrives at the site in five sections, along with the trailing edges, bolsters, teeter shaft, bearings, and ailerons. The blade sections and components are aligned, bonded, and assembled on the ground. The complete blade assembly is raised and secured to the yoke with a pair of yoke bearing caps.

Figure 22 illustrates the blade assembly being lifted by twin booms, to be mated with the supporting yoke in the nacelle, at the top of the tower. After the electrical and hydraulic connections are made, systems are checked and the wind turbine system is started for operating tests and customer acceptance.

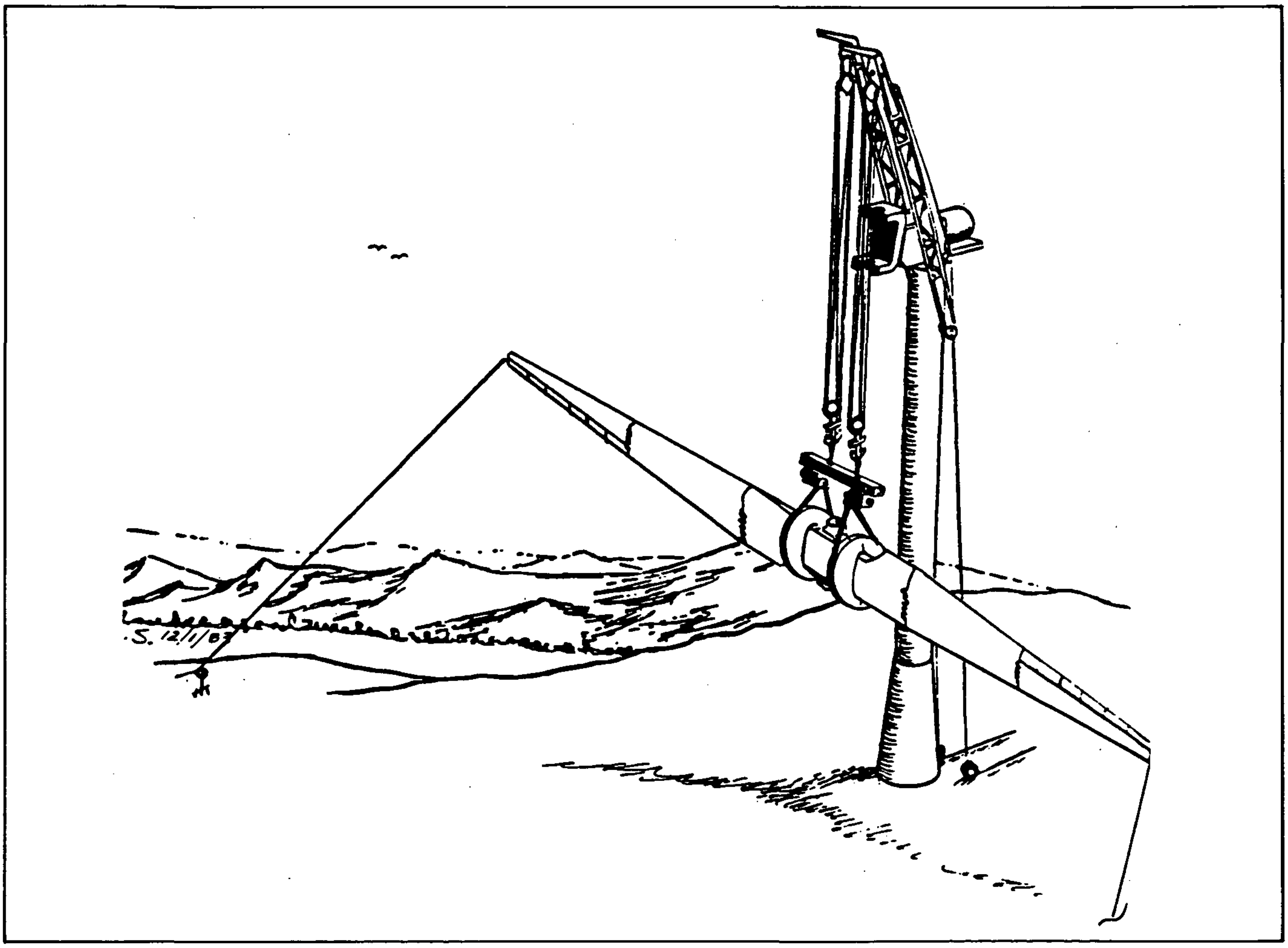

FIGURE 22. BLADE LIFT

CONCLUSIONS

When the MOD-5A program was brought to a close, all of the design objectives of the program had been achieved. The resulting wind turbine generator would produce three-phase, 60 Hz power for an electrical utility, with an average annual energy capture of 21.2 GW-hr in a region where the average annual wind speed is 14 mph. For a mature MOD-5A installed in 24-unit clusters the cost of this energy would be 3.69 cents/KW-hr., for the projected availability of 96%. It was designed to operate automatically and without an attendant, and the machine was expected to operate for 30 years. It could be manufactured and transported feasibly, using standard fabrication and construction techniques, and truck, rail or ocean shipping.

Unique features of the final design include a 400 ft. diameter laminated wood rotor, ailerons for controlling rotor torque and speed, an improved rotor support structure, and a 7.3 MW variable speed, constant frequency generator system. The size of the rotor was made possible by the use of finger joints for joining sections of the blade at the site. The blades are teetered at the center of rotation on an external steel yoke. This allows the primary load carrying blade structure to be continuous from tip to tip. The ailerons provide significant cost and weight savings over previously used torque control concepts. The non-rotating rotor support system reduces the susceptibility to fatigue failure in this area. The variable speed generator provides efficient two-speed operation to maximize energy capture. All these features represent advances in wind turbine development.

Although the MOD-5A prototype will not be built and tested as originally intended, the program made substantial contributions toward the commercialization of large-scale, utility-based, wind power. Extensive system and sub-system trade-off studies were completed. Significant improvements were made in wind turbine analytical techniques. Key computer codes were transferred to NASA. Test data was obtained to enable the confident design of wood laminate blades. Aileron feasibility was demonstrated by test and the aerodynamic data base needed for wind turbine applications was established. Most important, all of these results have been thoroughly documented. They will allow future development of large wind turbine systems to build upon the contributions made by the MOD-5A wind turbine generator program.

CLOSURE

This Executive Summary, Volume I, has presented an overview of the MOD-5A Wind Turbine Generator Program. The design is discussed in detail in Volumes II and III. The contents of these volumes are listed on pages following. Microfiche copies of these volumes are included in the back of this book.

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1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA CR-174734		

4. Title and Subtitle	5. Report Date
MOD-5A Wind Turbine Generator Program Design Report Volume I - Executive Summary	August, 1984
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
	10. Work Unit No.
9. Performing Organization Name and Address General Electric Company Advanced Energy Programs Department P.O. Box 527 King of Prussia, PA 19406	11. Contract or Grant No. DEN 3-153
	13. Type of Report and Period Covered Contractor Report
12. Sponsoring Agency Name and Address U.S. Department of Energy Conservation and Renewable Energy Division of Wind Energy Technology Washington, D.C. 20545	14. Sponsoring Agency Code DOE/NASA/0153-1

15. Supplementary Notes

Final report. Prepared under Interagency Agreement DE-AI01-79ET20305. Project Manager, T.P. Cahill, Wind Energy Project Office, NASA Lewis Research Center, Cleveland, Ohio 44135

16. Abstract

This report documents the design, development and analysis of the 7.3MW MOD-5A wind turbine generator covering work performed between July 1980 and June 1984. The report is divided into four volumes: Volume I summarizes the entire MOD-5A program, Volume II discusses the conceptual and preliminary design phases, Volume III describes the final design of the MOD-5A, and Volume IV contains the drawings and specifications developed for the final design.

Volume I, the Executive Summary, summarizes all phases of the MOD-5A program. The performance and cost of energy generated by the MOD-5A are presented. Each subsystem - the rotor, drivetrain, nacelle, tower and foundation, power generation, and control and instrumentation subsystems - is described briefly. The early phases of the MOD-5A program, during which the design was analyzed and optimized, and new technologies and materials were developed, are discussed. Manufacturing, quality assurance, and safety plans are presented. The volume concludes with an index of volumes II and III.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Renewable energy; Wind energy Wind power; Variable speed generator Wind turbine design; Wind turbine system; Wood rotor blades; Large scale wind turbine	Unclassified - unlimited STAR Category - 44 DOE Category - UC-60

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price*
Unclassified	Unclassified		

*For sale by the National Technical Information Service, Springfield, Virginia 22161